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A SYSTEM TO INTEGRATE UNMANNED UNDERSEA VEHICLES WITH A SUBMARINE HOST PLATFORM

by

Willard Calvert
Rachel Cohn
Gail Goodman
Brian Heidt
Joseph Lojek
Sarah Malecki
Brian Powell

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Prepared for: Chairman of the Systems Engineering Department in partial fulfillment of the requirements for the degree of Master of Science in Systems Engineering

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NAVAL POSTGRADUATE SCHOOL

Monterey, California 93943-5000

Daniel T. Oliver
President

Leonard A. Ferrari
Executive Vice President and
Provost

This report was prepared for the Chairman of the Systems Engineering Department in partial fulfillment of the requirements for the degree of Masters of Science in Systems Engineering and funded by Naval Sea Systems Command.

This report was prepared by:

Willard Calvert
Rachel Cohn
Gail Goodman
Brian Heidt
Joseph Lojek
Sarah Malecki
Brian Powell

Reviewed by:

Dr. Jeffrey Beach
Project Advisor

John Green
Project Advisor

Clifford Whitcomb, Ph.D.
Chair, Department of Systems Engineering

Released by:

Karl A. van Bibber, Ph.D.
Vice President and Dean of Research

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14. ABSTRACT

Submarines offer a capability to deploy and retrieve unmanned undersea vehicles (UUV) in littoral and blue water Areas of Operation while avoiding detection. Integration of the submarine and UUV through a launch and recovery mechanism offers unique challenges with respect to host submarine safety, UUV recovery, UUV replenishment and life-cycle costs. The Capstone team elicited launch and recovery system requirements from stakeholders and conceived four (4) advanced alternatives and a baseline alternative considered to meet the requirements. Through functional, cost, risk, modeling and qualitative analysis, this study assessed the value of each alternative to stakeholders. Of the concept alternatives explored, a high tech option featuring a carbon fiber structure, electro-mechanical pulse launch and recovery device and proximity vice contact battery charging and UUV stowage features provided the best value to the stakeholders for the investment. These results highlighted characteristics, including maintenance considerations, upgradeability, design for reliability and design for universal applications considered paramount for a successful system. Project lessons learned uncovered significant risk due to instability of UUV requirements as well as certification issues which adversely affect a submarine/UUV integration project. Early communications between key stakeholders must effectively address these short-comings.

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Submarines offer a capability to deploy and retrieve unmanned undersea vehicles (UUV) in littoral and blue water Areas of Operation while avoiding detection. Integration of the submarine and UUV through a launch and recovery mechanism offers unique challenges with respect to host submarine safety, UUV recovery, UUV replenishment and life-cycle costs. The Capstone team elicited launch and recovery system requirements from stakeholders and conceived four (4) advanced alternatives and a baseline alternative considered to meet the requirements. Through functional, cost, risk, modeling and qualitative analysis, this study assessed the value of each alternative to stakeholders. Of the concept alternatives explored, a high tech option featuring a carbon fiber structure, electro-mechanical pulse launch and recovery device and proximity vice contact battery charging and UUV stowage features provided the best value to the stakeholders for the investment. These results highlighted characteristics, including maintenance considerations, upgradeability, design for reliability and design for universal applications considered paramount for a successful system. Project lessons learned uncovered significant risk due to instability of UUV requirements as well as certification issues which adversely affect a submarine/UUV integration project. Early communications between key stakeholders must effectively address these short-comings.

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List of Abbreviations and Acronyms

AHP	Analytic Hierarchy Process
ALT	Alternative
AO	Area of Operation
A_O	Operational Availability
AoA	Analysis of Alternatives
C2I	Command, Control and Intelligence
CAIV	Cost as an Independent Variable
CINC	Commander in Charge
CNO	Chief of Naval Operations
CONOP	Concept of Operations
COTS	Commercial-Off-The-Shelf
DII	Defense Information Infrastructure
DT&E	Demonstration Test and Evaluation
EB	General Dynamics Corp. – Electric Boat Division
EMP	Electromagnetic Pulse
FMECA	Failure Mode Effects and Criticality Analysis
FOS	Family of Systems
HY	High Yield
IEEE	Institute of Electrical and Electronics Engineers
INCR	Increment
ISR	Intelligence, Surveillance and Reconnaissance

KPP	Key Performance Parameter
LCC	Life-Cycle Costs
LORA	Level of Repair Analysis
LOS	Line of Sight
LRS	Launch and Recovery System
LMRS	Long-Term Mine Reconnaissance System
LRS	Launch and Recovery System
MAC	Multiple All-Up Round Canister
MIL-STD	Military Standard
MTBF	Mean Time between Failures
MTBOMF	Mean Time between Operational Mission Failures
MOE	Measure of Effectiveness
MOP	Measure of Performance
MRUUV	Mission Reconfigurable Unmanned Undersea Vehicle
M&S	Modeling and Simulation
NGNN	Northrop Grumman Corp. – Newport News Shipbuilding
NUWC	Naval Underwater Warfare Center
NTA	Naval Tactical Analysis
OMOE	Overall Measures of Effective
OPSIT	Operational Situation
OT&E	Operational Test and Evaluation
OV	Operational View
QFD	Quality Function Deployment

REC	Re-Entry Control
RF	Radio Frequency
ROV	Remotely Operated Vehicles
SATCOM	Satellite Communications
SME	Subject Matter Expert
SOF	Special Operating Forces
SSN	Fast Attack Nuclear Submarine
SSBN	Ballistic Missile Nuclear Submarine
SSGN	Guided Missile Nuclear Submarine
SUBSAFE	Submarine Safety
TES	Test and Evaluation Strategy
TOC	Total Ownership Cost
TMA/TMI	Top Management Attention/Top Management Issue
TPM	Technical Performance Measure
TRL	Technology Readiness Level
TWH	Technical Warrant Holder
UHF	Ultra High Frequency
ULRM	Universal Launch and Recovery Module
UNTL	Universal Naval Task List
UUV	Unmanned Undersea Vehicle
VA	Virginia Class Submarine
VLS	Vertical Launch System
VPT	Virginia Payload Tubes

EXECUTIVE SUMMARY

This Capstone project focused on the considerations and interfaces needed to successfully field and support a system that would launch, recover, replenish, stow and transfer information between current and future Large Vehicle Class Unmanned Undersea Vehicles (UUVs) and host submarines, specifically submarines with the VA Class Block III payload tube concept. This system will provide a capability to support persistent–ISR missions identified in the UUV Master Plan of 2004 by providing stealthy information collection capabilities, threat and harbor monitoring, WMD identification and sea floor object reconnaissance.

To accomplish the project objectives, the Capstone team used a Systems Engineering approach to analyze and develop system requirements and functions which led to the establishment of five (5) proposed concept alternatives. These alternatives were compared and contrasted with respect to performance, life-cycle costs, risks and suitability through modeling and simulation, direct cost analysis and qualitative analysis.

Of the concept alternatives explored, Alternative 4 (a high tech option featuring a carbon fiber structure, electro-mechanical pulse launch and recovery device and proximity vice contact battery charging and UUV stowage features) provided the best value to the stakeholders for the investment. Alternative 4 demonstrated superior model performance times with an acceptable rate of success. Acquisition costs were mid-range while sustainment costs were comparatively low due to high reliability and maintainability of the structure, redundant features and lack of frictional wear issues.

Specific technologies for concept component packages and the pros and cons for the technologies were based on Capstone team experience, discussions with peer-groups

and available literature. Future technologies may result in alternative groupings that provide superior value to the stakeholder at equal or less investment. However, the Capstone team concluded that several characteristics, detailed below, are keys to any successful system:

- Structural components are the most significant cost driver, both in acquisition and maintenance. Solutions should consider mixed materials such as molding metallic parts into the composites at manufacture to increase strength at component attachment points while still providing a light-weight, corrosion-resistant and cost-stable structure that is upgradeable without extensive re-fabrication.
- Successful launch and recovery mechanisms must be adaptive to UUV size, shapes and materials and must minimize submarine dwell time. Mechanisms should consider ways to attract or repel the UUV without physical contact.
- Technology packages should focus on systems that multi-task and adequately function in the event of minor failures. Components that offer redundant functions and fault-tolerance increase overall reliability.

The Capstone team identified several lessons learned for consideration which may enhance follow-on UUV/submarine integration projects and studies:

- **Requirements Stability** - Stakeholders should consider re-visiting the mission and operational parameters established for persistent –ISR operations in the 2004 UUV Master Plan. Particular emphasis should be focused on endurance requirements for perceived missions and whether it is feasible, in the near term, to field UUVs that meet those endurance requirements and enable submarines to support those endurance requirements.

- **Submarine/UUV System Certification Issues –** Due to operational environment and contained structure, UUVs and their launch/recovery mechanisms can pose a widespread and detrimental effect to the host submarine and submarine personnel not seen with air or ground unmanned vehicles. While governing ASTM guides provide guidelines for the capabilities of UUVs, they do not specifically address constraints related to submarine launch and recovery platforms. Integration issues, particularly those related to Submarine Safety (SUBSAFE) require early and on-going teaming between submarine and UUV stakeholders.
- **Modularity/Flexibility -** UUV manufacturers continue exploration of technologies meant to break through constraints that limit current capabilities. As newer technologies affect UUV size, materials and capabilities, early and close relationships with UUV designers is paramount to ensure launch and recovery system functions support UUV design trends.

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I. INTRODUCTION

A. PROBLEM STATEMENT

1. Background

Submarines provide the Navy the ability to deliver effects or conduct operations without adversary warning or detection. However, due to many factors including draft, size, and personnel considerations, submarines do not operate on station for deployments longer than about 90 days and, in particular, cannot operate in littoral waters off an adversary's coastline. Submarine launched Unmanned Undersea Vehicles (UUVs) can help conduct missions and reduce the risk to manned platforms, while increasing the range and endurance of a mission.

In 2009, the Chief of Naval Operations (CNO) directed his staff to develop unmanned system plans for near-term (5 years) and mid-term (10 year) timeframes, as well as a 30-year vision. In parallel with the CNO staff planning efforts, the Director of Undersea Technology, SEA073, initiated a study, published as the UUV Roadmap, to coordinate Navy-wide UUV efforts and develop a plan for UUV operations from a variety of platforms. The 2004 UUV Master Plan documented a vision for unmanned undersea vehicles (Figure 1) and determined that Intelligence, Surveillance and Reconnaissance (ISR) operations was the most important mission for UUV military applications. Persistent–ISR capabilities support the "Sea Power 21" Pillars by providing stealthy information collection capabilities, threat and harbor monitoring, WMD identification and sea floor object reconnaissance (Figure 2). Large Vehicle Class UUVs, defined as multi-platform compatible vehicles, which displace approximately 10 long tons and are typically over 21 inches in diameter, is one type of UUV identified to support ISR missions. The Large Vehicle Class UUVs that support ISR operations generally have an on station time of at least 300 hours and a mission range of at least 75 nautical miles [UUV Master Plan 2004].

The increased size inherently provides Large Vehicle Class UUVs payload, power and endurance advantages over smaller UUVs.

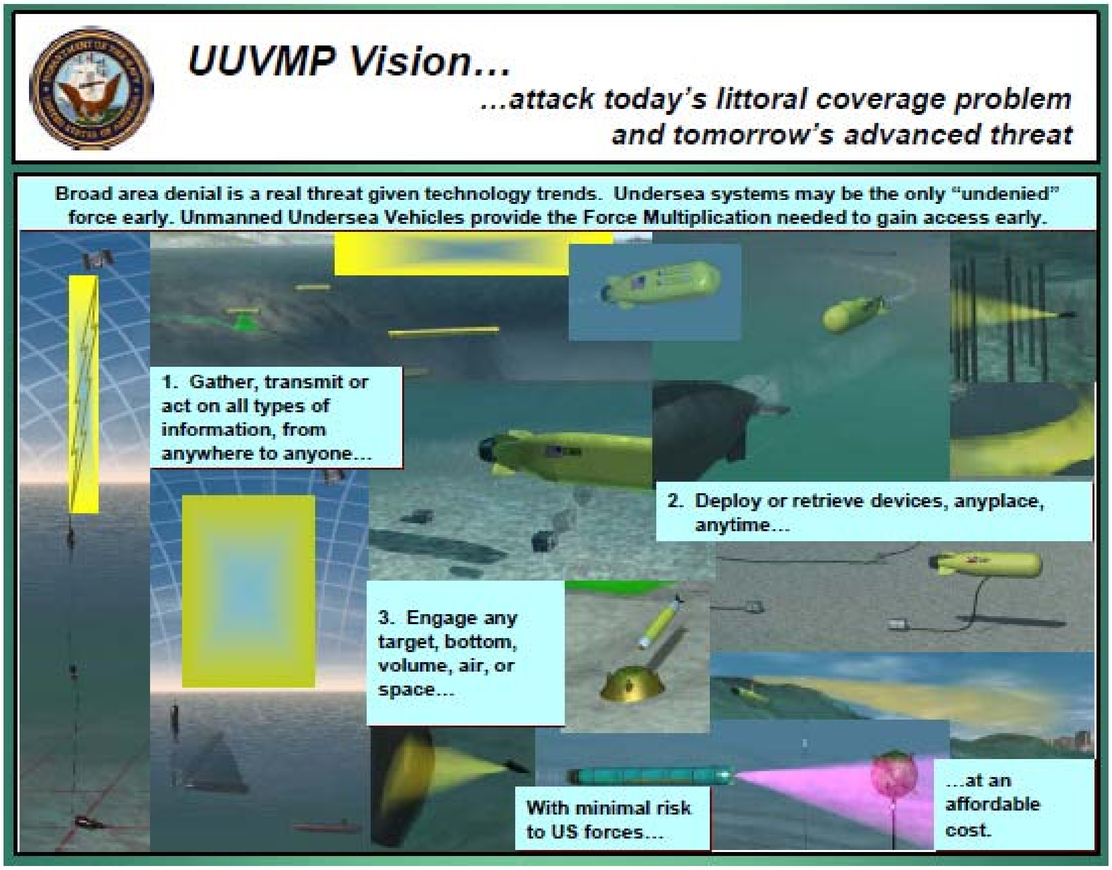


Figure 1 – UUV Master Plan Vision [UUV Master Plan, 2004]

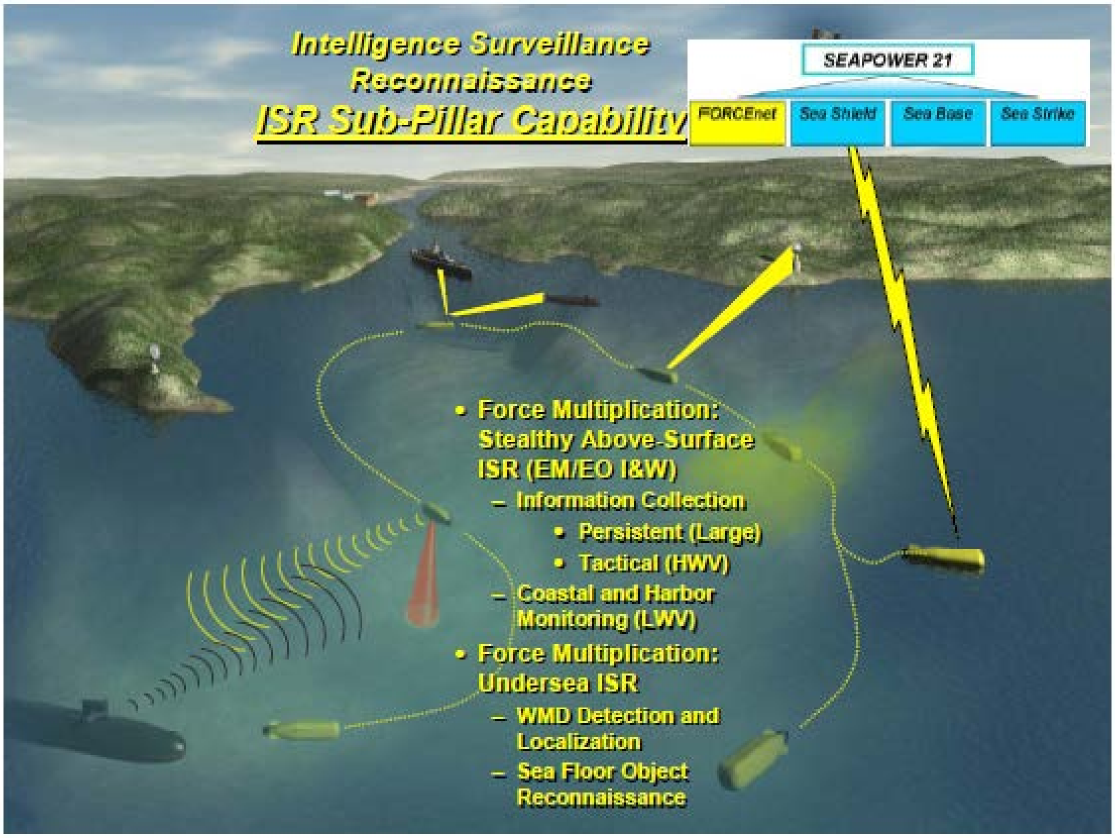


Figure 2 – ISR UUV Sub Pillar [UUV Master Plan, 2004]

2. Need Statement

Launching of UUVs from submarines has been accomplished using the host platform's 21-inch diameter torpedo tubes. The conversion of four ballistic missile (SSBN) submarines to guided missile submarines (SSGN) resulted in an added capability of launching and interfacing with larger diameter UUVs by utilizing the SSGN's 88-inch tactical payload tubes. Beginning with the construction of Virginia (VA) Class Block III fast-attack nuclear submarines (SSNs 784-791), this submarine class will be equipped with 2 SSGN-like payload tubes rather than the 12 smaller vertical launch tubes found on Block I and II VA Class submarine designs. This gives the Block III and later increments of the submarine class the ability to launch and interface with Large Vehicle Class UUVs. For submarine launched Large Vehicle Class UUVs to be an effective tool for undersea warfare persistent-ISR operations, a system is required to integrate the host submarine and the Large Vehicle Class UUVs. This system must provide launch, recovery, replenishment and communication capabilities without adversely affecting the certification of the host submarine for unrestricted operations.

3. Project Objective

Using System Engineering principles and following the guidance established in the Project Management Plan (Appendix A), the Capstone team developed the concepts and functions necessary and offered a conceptual preliminary design of a system that integrates the Large Vehicle Class UUVs with the VA Class Block III Submarine payload tube concept. The analysis focused on a family of systems (FOS) and their interfaces that supports launch, recovery, replenishment, communication with and stowage of a Large Vehicle Class UUV on a submarine with a VA Class Block III payload tube concept.

B. ASSUMPTIONS

This project sought to identify the functionality (and the physical architecture needed to accomplish the functionality) of a standard launch, recovery and communication mechanism that integrates with the external boundaries of the submarine launched Large Vehicle Class UUV and a host submarine which employs the VA Class Block III payload tube concept. Through analysis of the requirements, mission, functions, components and interfaces, the scope of this project was to identify the concepts necessary to define the interactions between the UUV and the host submarine. The Capstone team developed several key assumptions to establish the guidelines and boundaries of this research project:

- The Capstone team recognized that design and development of UUV systems is a rapid and dynamic environment and, due to the classified nature of future threat planning and assessment, only general missions, threats and scenarios were realistically and reasonably assessed. Additionally, it was considered acceptable that this project not decompose system functions and physical architecture into detailed designs where specific interactions between human operators, submarine communication systems and UUV control systems became classification sensitive.

- For the starting point of design and capability research, this project leveraged off of existing and similar concepts for a Large Vehicle Class UUV launched and recovered via torpedo tubes (Figure 3) and a SSGN large missile tube launch and recovery system (Figure 4). This project sought to improve upon these concepts.
- The main challenges of the project remained what they are for existing systems; namely power needs for replenishment of Large Vehicle Class UUVs, difficulties encountered with UUV recovery, impacts on host submarine safety and system operational parameters, which limit the effectiveness of existing concepts.
- The system-engineering approach employed on this project captured and verified the many divergent stakeholder needs associated with fielding of future UUV launch and recovery concepts and will provided a basis for examination and analysis of future UUV/host submarine integrated concepts with a concentration on performance and total ownership costs.
- To establish the "fixed" external boundaries necessary for interface, cost, performance and design examination, this project was specific for integration of a "standard" Large Vehicle Class UUV with VA Class Block III and later submarines only. This project did not examine Large Vehicle Class UUV integration with any other class of submarine. However, it is expected the results and conclusions of this

project would apply to any US Navy or foreign submarine which exhibits dimensional and functional characteristics similar to the VA Class Block III submarine payload tube concept.

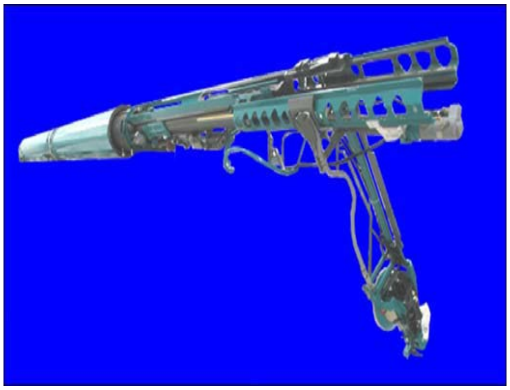


Figure 3 – AN/BLQ-11 Long-Term Mine Reconnaissance System (LMRS) (Torpedo Tube Launch and Recovery System) [White, D. P., 2007]

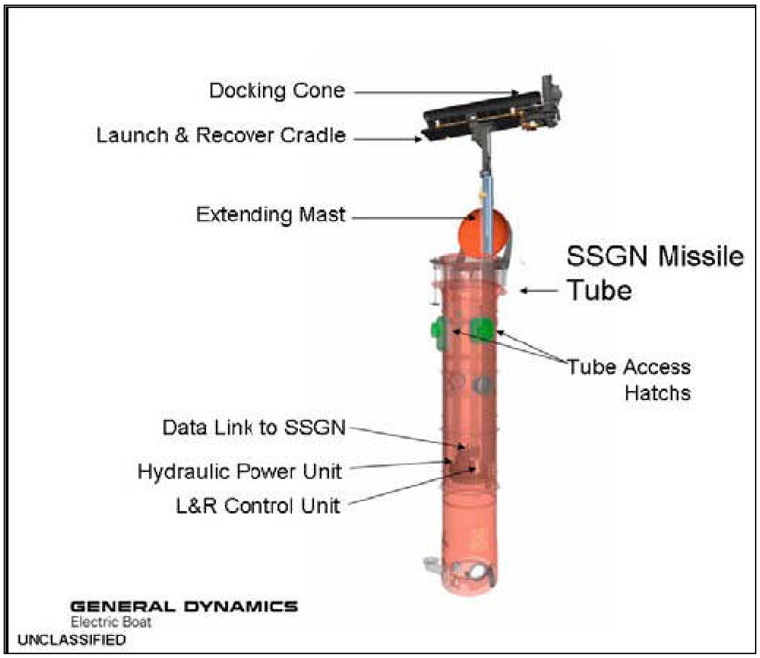


Figure 4 – Universal Launch and Recovery Module (ULRM) (SSGN Missile Tube Launch and Recovery System) [White, D. P., 2007]

C. SYSTEM ENGINEERING APPROACH

1. Overview

The Capstone team focused on the identification of and verification of stakeholder needs while applying a Systems Engineering approach in a phased plan strategy. To this end, the team delivered a System Engineering solution to satisfy the current need of the stakeholders seeking to launch, recover, communicate with, replenish and stow Large Vehicle Class UUVs with submarine host platforms, specifically the VA Class Block III submarine. The topics addressed herein outline the approach and structure to successfully define system requirements, functionality, synthesis and design. To mitigate risks and maximize stakeholder satisfaction, the active stakeholders and Subject Matter Experts (SME) were involved throughout the engineering process.

a. Systems Engineering Process Model

The Capstone team utilized the Institute of Electrical and Electronics Engineers (IEEE) System Engineering Process Model, Figure 5, to identify the stakeholder needs and deliver the best recommended solutions. The IEEE System Engineering Process Model has six process phases.

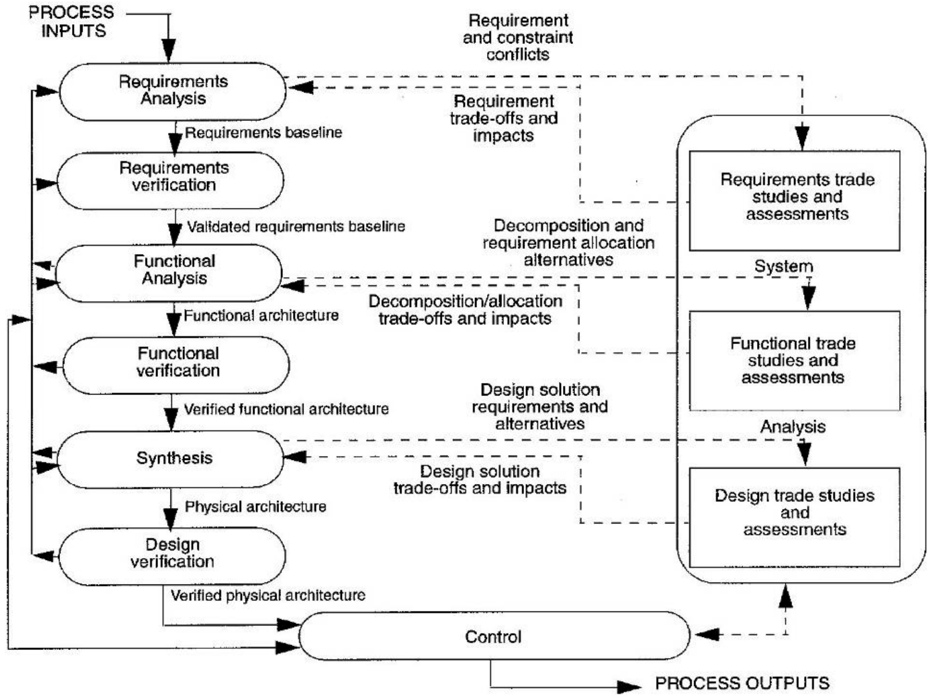


Figure 5 – IEEE System Engineering Process Model [IEEE Standard 1220, 1998]

2. Systems Engineering Process Phases

The process phases, shown in the IEEE System Engineering Process Model, Figure 5, and actions taken to accomplish the phases of the process model, are detailed as follows:

a. Requirements Analysis Phase

Input: Stakeholder needs

Output: Requirements baseline

Actions: Define Needs, Define Risks, Manage Requirements, Prioritize System Design, Assess and Trade-Off Requirements

The stakeholder needs were used to identify design requirements and prioritize system capabilities. During the stakeholder needs analysis, the stated need requirements were base lined.

System risks were identified throughout the development of the design process. Risk mitigation strategies were used throughout the process to avoid and manage the risks associated with the development of the system. System requirements were generated with the continuous involvement of stakeholders throughout all phases of the project. This supported requirement management and reduced the risk of misinterpreting the stakeholder needs, values and priorities. With the involvement of the identified stakeholders, system design capabilities and performance requirements were prioritized with the use of various system metrics and traced to their needs. The scaled level of priority supported future trade-off analysis when evaluating alternative solutions. Requirement trade-off analysis was performed to resolve conflicts, including funding, schedule, performance and quality needs. Risk levels and mitigations were used throughout the requirement trade-off analysis. The ultimate deliverable was a final assessment of system requirements that governed the design of the Large Vehicle Class UUV interface to the host submarine.

b. Requirements Verification Phase

Input: List of requirements for stakeholder verification

Output: Validated requirements baseline

Actions: Define System Functions, Conduct Functional Traceability, Validate Functions to Requirements

The establishment of the requirements baseline was followed by the functional analysis, which established the functional architecture and validated the requirements baseline. The requirements baseline was analyzed, and from the baseline, the top level functions were identified and the functional decomposition was performed with enough granularity such that the end state of each decomposition contains the backbone (and vertebrae) of each of the top level functions. The functions that were not directly concerned with the engineering aspects of the project were decomposed to lesser degrees of granularity due to the focus/bulk of the work needing proper definition in the engineering realm. A functional hierarchy of system requirements was drafted so requirements were traceable to the particular stakeholder need. Information flow block diagrams were established and functions were allocated to system components and performers.

c. Functional Analysis Phase

Input: Validated requirements baseline

Output: Functional needs and requirements

Actions: Create Alternative Design Concepts, Examine Feasibility, Score Alternative Design Concepts, Conduct Cost-Benefit Analysis, Conduct Functional Trade Studies & Assessments

Alternative design concepts were created using the base lined requirements proposed by the stakeholders. The team members prioritized system capabilities so that critical functions and their sub-functions supported the system's mission. Quality Functional Deployment (QFD) models with weighted values were used to assess the proposed alternative design solutions and establish component concepts that could perform the required functions. The alternative designs were evaluated for design feasibility with regard to budget, acceptable risk and schedule. Feasibility criteria defined by the stakeholders and team members were used to screen all alternative design concepts. Failure to satisfy the feasibility criteria would deem the concept to be infeasible and, as such, the alternative was discarded to reduce strain on the project's resources, so that time and value assets were not wasted. The team used metrics to score concept design alternatives. The active stakeholders participated with the team to verify and validate that the final conceptual alternatives satisfied the needs at an acceptable level of risk. Any requirement conflict observed was addressed and adjudicated with the involvement of stakeholders.

A cost-benefit analysis was performed to formally identify and assess benefits associated with design alternatives in addition to the costs anticipated from the project. The cost analysis evaluated the value associated with the system over its life cycle in relation to its stakeholder benefit. The cost-benefit analysis was one of the factors that resulted in a recommended design for prototyping that offered the greatest value to the stakeholders while meeting all design Key Performance Parameter (KPP) and schedule requirements. Once the functional analysis was accomplished, the functional trade studies and assessments of the top level functions and their decomposition were conducted. The analysis looked at tradeoffs for identified functions and evaluated related functions that may not have been originally identified to see if they were useful or necessary for the efficient completion of the project (e.g. is anything missing from the functions? Could there be an alternate function that provides a better solution? Have the engineering functions been decomposed such that their bottom level provides the building blocks to meet the stakeholder needs with the top level function?). The results of the trade-offs were analyzed and the best solution was worked into the final functional decomposition.

d. Functional Verification Phase

Input: Functional Needs

Output: Verified Functional Needs and Concepts

Actions: Conduct Life-Cycle Cost Analysis, Conduct Model Simulations, Conduct Sensitivity Analysis, Analyze Performance and Costs of Concepts

From the functional needs/requirements, the functional verification took place. This analyzed the top level functions and their decomposition to make sure that the chosen architecture met all stakeholder requirements. Modeling was utilized to simulate the Operational Situations (OPSITs) which defined the theater of operation and mission requirements. Simulation results provided the team with critical information pertaining to system performance and operation. Aspects such as, but not limited to, operational availability, successful launch, successful recovery, system causality, communication failure and other potential risks were analyzed to evaluate the capability of alternative designs. Results were utilized to weigh design selection. A sensitivity analysis was performed to evaluate the system design parameters relationships and the results of the baseline analysis to ensure that the overall life-cycle costs and model generated were valid. Critical input parameters were identified that directly impact cost (more than 10% of total cost). The identified critical input parameters were evaluated in a model to simulate the cost impact associated with the model's output. Critical input parameter variations were modeled over a designated range which considered appropriate distributions for the system design critical items. It was essential for the analyst to be confident with the identified critical inputs interrelationships, their impact on cost, the sensitivities of the model in the identification of cause-and-effect relationships and the potential areas of risk associated with the Life-Cycle Costs (LCC) analysis results. The analysis resulted in the sensitivity of a system's LCC in relation to potential variations such as but not limited to operational availability, mean time between maintenance, and system casualties.

e. Synthesis Phase

<u>Input</u>: Verified Functional Architecture

<u>Output</u>: Physical Architecture

<u>Actions</u>: Initiate Design Process, Conduct Design Trade Studies & Assessments

Once the functional need and requirements were verified, the design process began to establish the physical architecture. Here, the interface documents were developed as well as the specifications for the hardware and software. Utilizing the developed interface documents, the hardware and software design and development would progress. Hardware and software components were researched and conceived to conceptual, performance and interface standpoint. From the physical architecture, the last of the trade-offs were conducted. The design trade-off examined the way the design was assembled and explored alternate means of construction (e.g. did we pick the most efficient way to integrate the Large Vehicle Class UUV and the host submarine? What is the relationship between different combinations of hardware and reliability of successful UUV launch/recovery?). From the explored trade spaces, the most efficient solution was put forward and finalized as the physical architecture for the UUV Launch and Recovery System (LRS).

f. Design Verification Phase

<u>Input</u>: Physical Architecture

<u>Output</u>: Verified Physical Architecture

<u>Actions</u>: Accomplish Verification, Decision-Making and Conclusion Analysis

The Design Verification phase implemented the test and evaluation strategy to make sure that the physical architecture met all derived and stated stakeholder requirements. The successfully executed test plan, based on the system's requirements verification matrix and the passing of all tests results, verified physical architecture that was ready for detailed design and eventual production.

II. REQUIREMENTS ANALYSIS AND VERIFICATION

A. STAKEHOLDER NEEDS ANALYSIS

1. Background

Stakeholder needs analysis captured the functions, attributes and relationships of the system proposed to meet the perceived capability gap. [Blanchard & Fabrycky, 2006, pg. 57-59] The results of needs analysis were a set of requirements based on a solid foundation of customer desires to ultimately create a system that not only functions as the engineers expected, but also accomplishes the goals, either expressed or implicit, by the stakeholders.

Upon initial review, the needs for this project can seem to be rather basic; develop the systems required for a submarine to launch, control and recover Large Vehicle Class UUVs. However, such a system may endure a costly and short life if it is simply developed to the personal whims, political pressures or particular interests of one or a few stakeholders. Therefore, the focus on needs analysis during this project was to examine as many credible sources as possible and develop many varied and, at times conflicting, needs from these sources. Upon determination of the functions, attributes and relationships, or the "wants" required for the system, the team translated these into more specific system-level requirements. To ensure the team captured the intent of the customers, the system-level requirements were documented and verified against the clear statements of intent from interviews and literature. The outcome of this process allowed the team to develop a ranked and weighted list of Stakeholder Requirements for the system that supports not only immediate needs, but also potential UUV scenarios in the future.

2. Methodology

The team used their experience, discussions with proxy stakeholders (Subject Matter Experts or SMEs), and literature research to determine the stakeholder needs and value system associated with the needs. These needs were then ranked using an Analytic Hierarchy Process (AHP). This AHP uses pair-wise comparisons to rank the stakeholders needs. Each team members used the information obtained from the SMEs, along with the literature research and team member experience to conduct a pair-wise comparison of the stakeholder needs. The average of the team member's pair-wise comparisons was used to determine the priorities of the needs by assigning a weighted value to each need. These rankings were used when determining the system performance objectives, the KPPs, and the component requirements and risks for the conceptual design alternatives.

3. Stakeholders

There are two categories of Stakeholders, identified in Table 1, active and passive. Active stakeholders directly influence the requirements development phase of the project while passive stakeholders provide indirect influence into project requirements development.

The team met with the active stakeholders as practical and used feedback from these active stakeholders to verify the conceived system requirements. Their validation of the proposed requirements resulted in the team's identification of the verified requirements baseline.

The passive stakeholders were existing entities with interests and/or policies concerning UUVs and UUV missions. The passive stakeholders' needs were derived from the literature published directly by stakeholders and their representatives or literature published by experts in the field. The literature research identified several areas of interest with respect to deployment, replenishment and retrieval of UUVs from submarines.

<u>Safety</u>:

- Past systems "did not address Submarine Safety (SUBSAFE) issues or field usable systems. Current systems Mission Reprogrammable Unmanned Undersea Vehicles (MRUUVs) also will not address those long-standing safety issues and will not field a usable system by 2013." Additionally, "the development of (systems) to be launched from SSN torpedo tubes is difficult and requires design compromises." [Button, 2009]
- "Safety justification is likely to be harder if divers are required to work in and outside (an external launch, recovery and stowage mechanism)." [Hardy, 2008]

<u>UUV Recovery</u>:

- "Recovery is arguably more difficult when the submarine is in transit." [Hardy, 2008]
- It is "very unlikely to be able to retrofit (an enlarged torpedo tube concept) system into an existing submarine." [Hardy, 2008]
- Large diameter UUV challenges with respect to operations include "Contact avoidance with high traffic density including low signature fishing trawlers and high speed vessels" (requires considerations for rapid recovery). [Ashton, 2010]

<u>UUV Power Challenges</u>:

- "Energy has long been a major consideration due to its effect on the ultimate performance of extended vehicle missions." [Fletcher, 2005]
- Forward ends of "SSN submarines lack electrical power distribution systems needed to charge large, battery powered UUV." [Button, 2009]

Concerns for Total Ownership Costs:

- "The size and number of vehicles to be used, the overall system costs, and the interchangeability of modules all need to be considered as a critical part in developing the needed capabilities." [Fletcher, 2005]
- The "technology (of UUVs) has not lived up to where the Navy thought it was going to be at this point. If you want autonomous vehicles underwater, you have to advance the technology further before it is really capable - RADM Hilarides, Program Executive Officer (PEO) Submarines" [Fein, 2007]

Table 1 – Project Stakeholders and Needs

Stakeholder	**Needs**
Project Advisors (Active)	Ensure successful completion of the Capstone project
Launch and Recovery Mechanism End Users (Passive)	Operating Parameters and Capabilities, Safety, Reliability, Maintainable, Stealth
UUV Manufacturers (Passive)	New Platform for Equipment – Increased Market Share, Cost, Long-Term Commitment
Host Submarine Force Operators (Passive)	Flexible UUV Missions, Interoperable, Reliable, Safety
Naval Intelligence Community (Passive)	Data Transfer Security and Range, Interoperability, Persistent ISR Support
Naval Sea Systems Command - (Technical Concerns) (Passive)	Safety, Reliability, Operational Capabilities
Office of the Chief of Naval Operations (Passive)	Affordability, Flexible UUV Missions, Safety, Performance
System Logistics and Maintenance Suppliers (Passive)	Long Term Commitments, Total Ownership Costs, Reliability
Program Offices (Host Sub & UUV) (Passive)	Operational Parameters, Flexibility, Support Multiple Needs, Long-Term Commitments, Safety, Total Ownership Costs

Figure 6 provides a hierarchical chart, which illustrates the passive stakeholder's relationships and interactions. In Figure 6, the stakeholders are color coded to reflect Technical Authority (Red), Operational Authority (Green), and Program Authority (Gray).

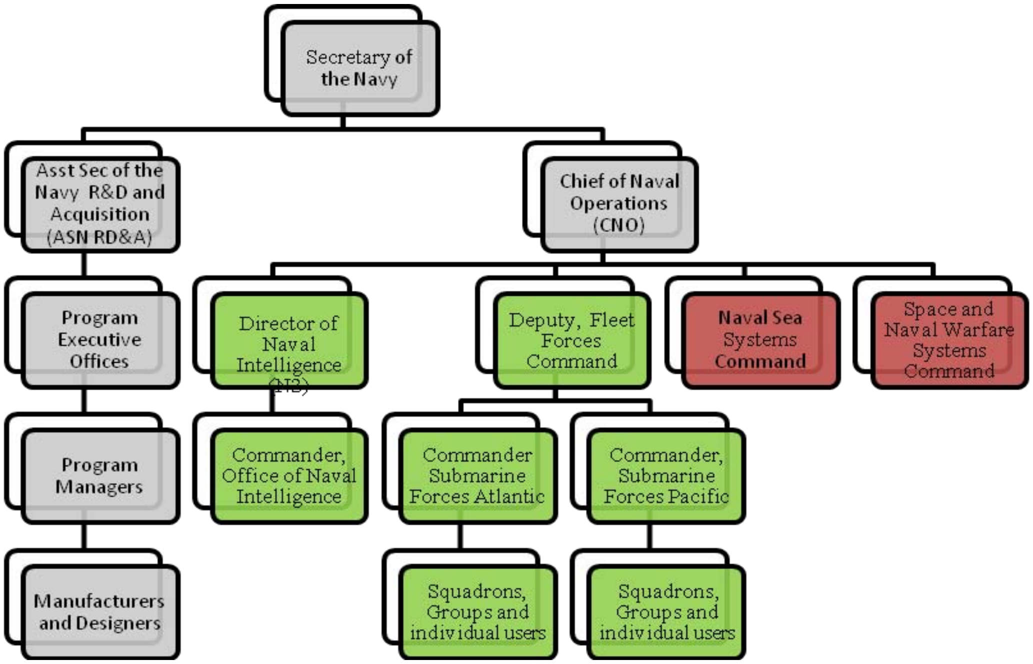


Figure 6 – Hierarchal Representation of Passive Stakeholder Relationships

In addition to the passive stakeholders identified needs, the team interviewed SMEs with current or past interests in Large Vehicle Class UUV programs. Although the resultant needs identified from some of these interviews constituted personnel opinions and/or interests in specific aspects of UUV programs, taken as a whole, these interviews provided the team invaluable information as to the perception of programs as well as exposed gaps and liabilities in past attempts to integrate UUVs and submarines. Table 2 provides a synopsis of the results from team interviews with SMEs. These SME results were consistent with the needs analysis of the stakeholders developed by the team through literature research and identified in Table 1.

Table 2 – SME Interviewees and Results

Name	Date	Organization	Title	Key Points
Mr. Jon Erickson	30 Sep 2010	SEA 073, Undersea Technology Office	073RX	• Guidance on the key technical points
Mr. David White	01 Oct 2010	Littoral and Mine Warfare Design and Systems Engineering	Deputy Director SEA 05LB	• Recovery system is key • Power is constraint • Desire a standard UUV which could be configured with multiple sensors
Mr. Steve Southard	08 Oct 2010 And 16 Mar 2011	NAVSEA 05T Technology Group (This organization is responsible for integration of new technology into the navy)	SEA 05T11, Division Head Technology Transition Division	• Support additional power requirements (recharging) or communications be extendable from 100 nm to 200 nm. • Use set based design approach to develop a range of possibilities to be included in specifications
Dr. Norbert Doerry			Technical Director	
Mr. David French	18 Nov 2010	NUWC N82	Technical Warrant Holder (TWH) for Unmanned Undersea System	• Communications – Direct UUV/host sub communications hard. Recommend host sub communication with satellite and one-way communication to UUV. • Off-board: Acoustic Communications Issues - robustness, range, bandwidth, content of data messaging • Off-board: RF or SATCOM with UUV, i.e. @ PD • Launch and Recovery: Mechanical, secure of vehicle (i.e. stow) shock, vibrations • CONOPS - platform speed for communications, platform speed for L&R, Communication reliability during L&R, water space mgt...., depth of operations. • UUV Certification (the biggies) – shock, energy (stow, charge, discharge, out gassing, etc...), implodable volumes (limits operational depth for L&R)

Table 2 – SME Interviewees and Results (Continued)

Name	Date	Organization	Title	Key Points
Mr. John Babb	17 Nov 2010	NUWC	Director, Conform Office, National Workload Manager – Undersea, Warfare Systems (previous worked Large UUV integration into SSGN)	• Mission profile needs to be down loaded by sub crew and installed into UUV prior to launch. • Work could be done on UUV with portable equipment – maintenance laptops. • LDUUV launched from back of ship. • UUV would have to be controlled from submarine (or surface ship) – fiber optic or acoustic interface. • Sensor data transferred to sub, sensor field or to another device, Hydro Acoustic Information Link (HAIL) is one system. • Digital acoustic communications with encryption. • Ship might work with a homing device. Look at ASDS, or DSRV. • A cradle might be installed topside • Theoretically, UUV could be re-launched from a submarine • A UUV operator can only control one UUV at a time unless they were working in a leader/follower situation.
Mr. Carlos Galliano	19 Nov 2010	NUWC N412 Payload and Payload Integration Department Chief Engineer	TWH for Undersea Launcher Systems	• UUV launcher needs interface to Weapons control console which causes the gas generator to fire. • MAC would be removed for the large UUV to be installed with launcher interface or else space restrictions would limit size to tomahawks • Restraint system would need to meet Grade B shock. • Provided an integration checklist which included such things as Physical Characteristics, environmental considerations, material considerations
Cmdr William B. Smith	15 Mar 2011	OPNAV N2N6F2	Head of Undersea Capabilities Branch	• Goal is first mission ready of LDUUV by 2017 with 30 days up to eventual 120 day endurance. Lengths of 20 feet to 45 feet, increased autonomy and redundancy. • Submarine host platform considered desired but not exclusive.
Dr. Edward Ammeen	15 Mar 2011	PMS 450 Program Office, VA Class Submarines	PMS 450 Representative for ULRM/ VA Class Integration Team	• Block IV and V VPT designs still under review. • UUV "mission creep" presents problems. Still potential tech issues with fielding on VA Class sub. • Greater teaming with UUV manufacturers would be beneficial. • Power technologies of a primary concern (safety/support).

-4. Analysis of Interviews/Research

a. Operational Setting

Submarine based large UUV systems provide a broad spectrum of ISR collection capability to support joint combatant forces in worldwide peace, crisis, and wartime operations. As discussed in the UUV Master Plan of 2004, "UUVs are uniquely suited for information collection due to their abilities to operate at long standoff distances, operate in shallow water areas, operate autonomously, and provide a level of clandestine capability not available with other systems." The capabilities of the UUV systems, coupled with the host submarine, provide for adaptive real time planning of current operations to include; monitoring enemy offensive and defensive positions, deception postures and combat assessments. This includes missions in support of battle assessment and the global war on terror. This system of systems will provide a rapid turnaround of raw data to aid a robust targeting cycle. Figure 7 below provides examples of threats and consequences, which could be deterred /mitigated by persistent-ISR UUV operation in a littoral area.

Somali Pirates [Dollard, 2009]

Underwater Ordinance (WMD) [AMPRO, 2010]

USS Cole Bombing [Maritime Quest, 2000]

Figure 7 – Threats Suited to Deterrence by Persistent-ISR UUV Operations

VA Class Block III submarines will be aligned under Commander, Submarine Forces Command/Submarine Force Atlantic/Allied Submarine Command and Commander Submarine Forces Pacific and assigned to an Atlantic or Pacific Fleet Squadron (e.g., Norfolk or New London, and Pearl Harbor). Figure 8 and Figure 9 provide a view of this command structure. Submarine commands are organized by operations and maintenance. All personnel will have a commitment to deploy in support of tactical operations or other tasking. The capability to support launch, replenishment and recovery of a Large Vehicle Class UUV from a VA Class Block III submarine will provide twenty-four hour, high-quality sensor coverage of a critical Area of Operation (AO), giving the theater Commander in Charge (CINC) intelligence advantages over potential enemies and threats.

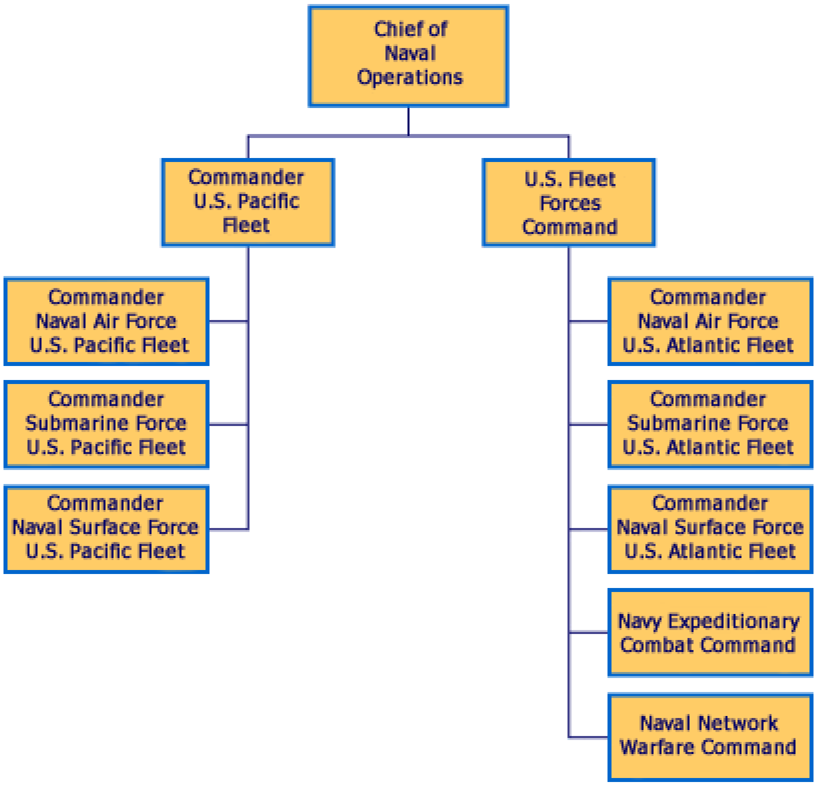


Figure 8 – Naval Command Structure

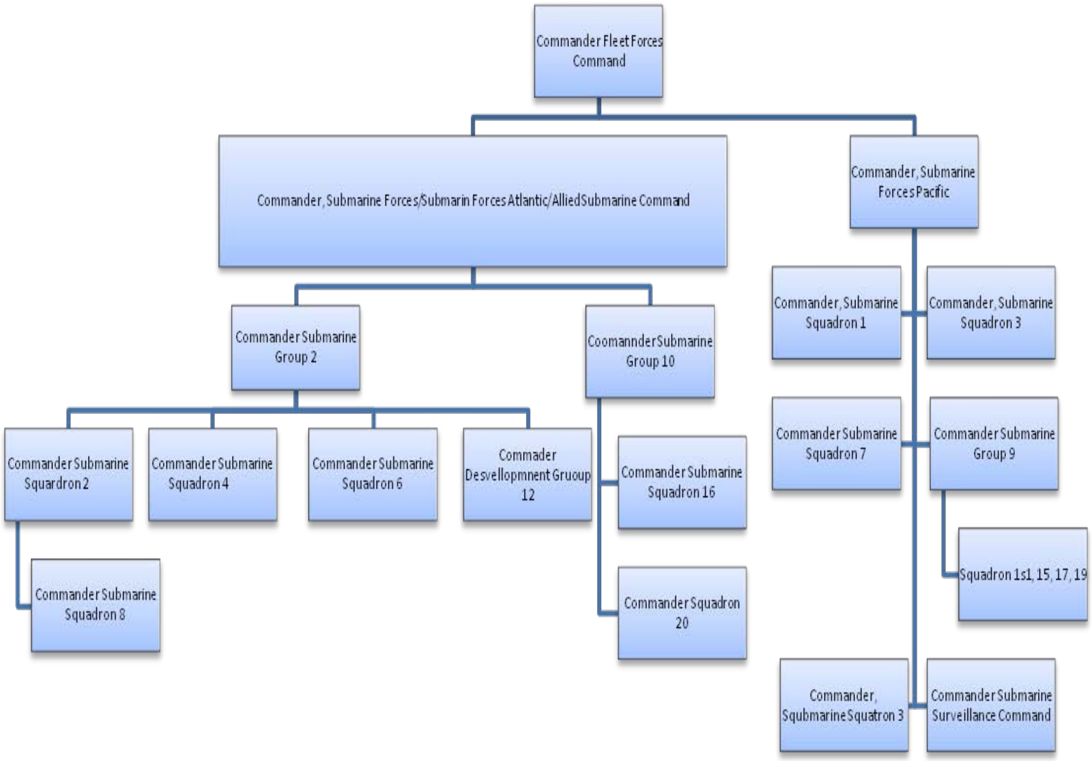


Figure 9 – Submarine Force Organization Structure

b. System Functionality and Tasks

The Uniform Navy Tactical Task List [UNTL, Jan 2007] was utilized to focus stakeholder wants and desires into a context of standard tasks the UUV/Launch and Recovery Mechanism/Host Sub FOS should perform. This hierarchy of tasks, outlined in Table 3 below, provided an initial basis for a concept of operations for the FOS and supported future functional and architectural development. It provided starting points for the team to develop measures of performance (MOP) for the launch and recovery system functions and assisted in defining achievable and clear needs from interview responses and literature.

Table 3 – Hierarchy of System Tasks

Naval Tactical Task (NTA)	Description
1.	DEPLOY/CONDUCT MANEUVERS
1.1	Move Naval Tactical Forces - [Move naval units and their systems from one position to another in order to gain an advantage or avoid a disadvantage]
1.1.2	Move Forces
1.1.2.5	Employ Remotely Operated Vehicles (ROVs)
1.2	Navigate and Close Forces – [Determine track for movement of naval forces to overcome challenges]
1.2.8	Conduct Tactical Reconnaissance and Surveillance
2.	DEVELOP INTELLIGENCE
2.2	Perform Collection Operations and Management – [Gather data, information and previous intelligence to satisfy identified requirements]
2.2.2	Collect Tactical Intelligence on Situation
2.2.3	Perform Tactical Reconnaissance and Surveillance
6.	PROTECT THE FORCE
6.1	Enhance Survivability – [Protect personnel and resources from enemy and friendly operations and systems and natural occurrences]
6.1.1	Protect Against Combat Area Hazards
6.1.2	Conduct Perception Management

Four (4) main tactical tasks defined the purpose of the UUV/Launch and Recovery Mechanism/Host Sub family of systems:

- Move Naval Tactical Forces
- Navigate and Close Forces
- Perform Collection Operations and Management
- Enhance Survivability

Team analysis of these tasks determined top-level functions performed by the LRS must include, as a minimum, launch, recover, communicate, replenish and stow. With respect to these functions, team members articulated system needs and ensured that needs defined for the project did not encompass an attribute outside the bounds of the LRS. For instance, the Special Operations Command - Naval Science and Technology Strategic Plan of 2009 [USSOCOM, 2009] recognize that advanced power systems are needed to support persistent-ISR missions with UUVs. Concepts may include larger, renewable systems, which place more demand on UUV charging sources. However, this project's scope did not include development of new power systems, a component inherent to UUVs themselves, but instead focused on flexibility of the LRS to support future concept changes and upgrades.

c. Stakeholder Value System

To support development and ranking of stakeholder needs by the Capstone team, a stakeholder value system was established. The stakeholder value system reflected not only the needs of the stakeholders, as determined through literature search and interviews, but also assigned an importance to each need with respect to other needs. The team identified the four (4) most important stakeholder's needs as:

- Operational Safety
- Support Increasing Power Demands
- Launch and Recovery Performance
- Minimization of Life Cycle Costs (LCC) (Acquisition, Maintainability and Reliability Considerations)

5. Conclusions

Using the results of stakeholder needs analysis, the team developed a list of requirements for the system. To rank the importance and weight the requirements, each team member accomplished a pair-wise comparison, using the stakeholder values and team member knowledge/experience. The cumulative results of the pair-wise comparisons are provided in Figure 10. Figure 11 displays the ranked and weighted stakeholder needs in descending order of importance, which demonstrated a consistent reflection of the established value system.

		1. Flexible to accommodate multiple size/shape UUVs	2. Support multiple packages/launches simultaneously	3. Accommodate large power sources/re-charging	4. System Weight	5. Affordable	6. Resist shock and noise conditions	7. Launch/recover performance parameters (time/stealth/moving sub)	8. Reliable	9. Host ship safety	10. Maintainable at Sea	11. Interface communications	
		1	2	3	4	5	6	7	8	9	10	11	Weight
1. Flexible to accommodate multiple size/shape UUVs	1	1	2.930	0.268	1.690	1.274	0.908	0.725	0.342	0.303	1.152	1.295	0.073
2. Support multiple packages/launches simultaneously	2	0.341	1	1.226	1.060	0.620	1.255	0.962	0.358	0.454	0.374	0.744	0.052
3. Accommodate large power sources/re-charging	3	3.733	0.816	1	3.179	2.255	1.748	1.445	1.687	1.163	2.251	0.783	0.123
4. System Weight	4	0.592	0.944	0.315	1	1.838	1.738	1.337	0.770	0.239	2.231	0.665	0.072
5. Affordable	5	0.785	1.614	0.444	0.544	1	1.944	1.854	1.040	0.324	2.667	2.667	0.091
6. Resist shock and noise conditions	6	1.101	0.797	0.572	0.575	0.514	1	2.345	2.962	1.549	2.929	2.250	0.102
7. Launch/recover performance parameters (time/stealth/moving sub)	7	1.379	1.040	0.692	0.748	0.539	0.426	1	3.393	1.741	3.179	4.076	0.112
8. Reliable	8	2.921	2.796	0.593	1.298	0.961	0.338	0.295	1	0.497	3.571	2.135	0.101
9. Host ship safety	9	3.301	2.205	0.859	4.186	3.084	0.646	0.574	2.013	1	5.048	4.786	0.170
10. Maintainable at Sea	10	0.868	2.671	0.444	0.448	0.375	0.341	0.315	0.280	0.198	1	1.992	0.055
11. Interface communications	11	0.772	1.343	1.278	1.504	0.375	0.444	0.245	0.468	0.209	0.502	1	0.050

Figure 10 – Cumulative Pair-Wise Comparison Results

Figure 11 – Ranked and Weighted Stakeholder Requirements

B. FUNCTIONAL ARCHITECTURE

1. Background

Once functional, performance, interface, and other requirements were identified, a functional analysis was performed to form a coherent description of system functions and performance, in the form of a functional architecture. This was accomplished by arranging functions in logical sequences, decomposing higher-level functions into lower-level functions, and allocating performance from higher- to lower-level functions.

In order to do this, functional hierarchy diagrams were first developed. These diagrams identified top-level functions, and successively define lower-level functional and performance requirements at ever-increasing levels of detail. This was done until there was sufficient detail to provide design and verification criteria to support the integrated system design. These diagrams were used to trace the requirements back to the stakeholder needs.

Integration Definition for Function Modeling was also performed, resulting in IDEF0 models. IDEF0 models defined process and data flows. They were composed of functions, and data and objects that inter-relate those functions. IDEF0s illustrated controls, inputs, data or objects acted upon by inputs, and mechanisms that provided supporting means for performing a function.

Finally, Enhanced Functional Flow Block Diagrams (EFFBs) were developed. These described the systems functions and the order in which they are to be executed.

2. Architectural Views and Products

The LRS functions were decomposed and the architecture of the system was created. The systems engineering tool, CORE®, by Vitech Corporation, was used to conduct the analysis. The analysis consisted of mapping functions, operational activities, performers, and requirements to each other to ensure all attributes correlated and to determine if any gaps existed. Several Department of Defense Architectural Framework (DoDAF) views were created to display this information.

a. System Functional Hierarchy

The team analyzed the functions that were derived in the requirements analysis. It was determined that the LRS has four top-level functions and all other functions are sub-functions of these. The top-level functions for the LRS are: “Launch”; “Recover”; “Replenish” and “Maintain”.

Launch Functional Hierarchy

Launch - This function prepares the LRS and then executes the launch of the UUV from the HostSub Payload Tube. The launch function consists of initiating the launch; commutating with the external systems which it interfaces (HostSub and UUV), to upload mission data; obtaining the HostSub environmental data and then using this data to determine system readiness; and finally executing the launch of the UUV. The launch functional hierarchy is displayed in Figure 12.

1.0 Launch

- 1.1 Initiate Launch Sequence
- 1.2 Communicate
  - 1.2.1 Establish LRS - Host Sub
  - 1.2.2 Establish LRS - UUV Communications Link
  - 1.2.3 Download ISR from HOSTSUB
  - 1.2.4 Upload ISR Data to UUV
- 1.3 Obtain Environmental Information
  - 1.3.1 Determine Host Sub/UUV Depth
  - 1.3.2 Determine threats (geological/enemy)
  - 1.3.3 Determine Host Sub/UUV Speed
- 1.4 Determine System Readiness
  - 1.4.1 Receive indication of UUV(s) readiness level
  - 1.4.2 Perform Self-Check of LRS
  - 1.4.3 Determine LRS Ready Status
  - 1.4.4 Communicate (to host ship) LRS ready to launch
  - 1.4.5 Receive indication of Host Sub readiness level
- 1.5 Execute Launch
  - 1.5.1 Unsecure/unlock LRS from tube
  - 1.5.2 Extend LRS
  - 1.5.3 Release UUV(s)
  - 1.5.4 Retract LRS
  - 1.5.5 Resecure/lock LRS in Payload Tube

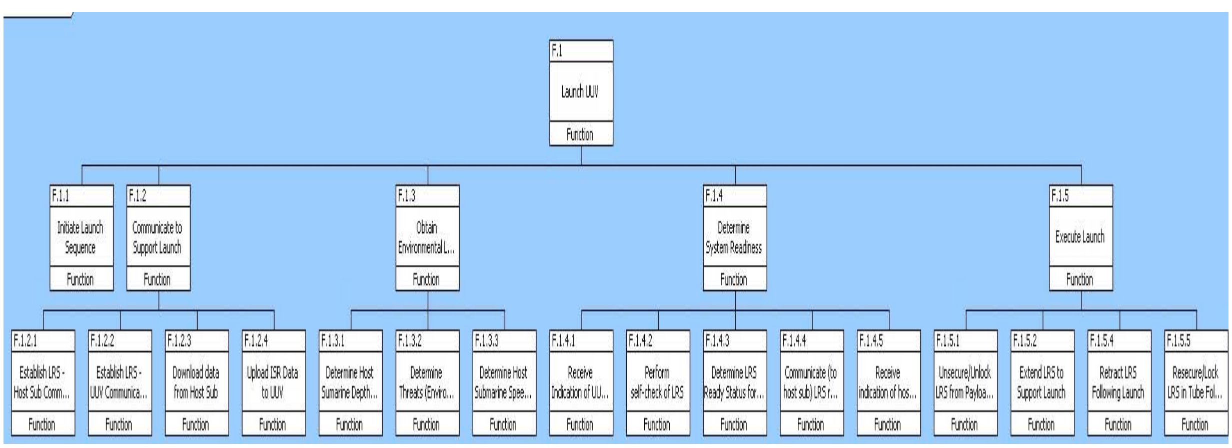


Figure 12 – Launch Functional Hierarchy

Recover Functional Hierarchy

Recover - The recovery function prepares the LRS and executes the recovery of the UUV until the UUV and LRS are stowed in the HostSub Payload Tube. The recovery function is similar to the launch function in that it established communications with the HostSub, obtained environmental information and assesses whether the LRS is ready to recover the UUV. The recover function also has the capability to execute the recovery by extending the LRS, activating the location device, capturing the UUV and then retracting the recovery mechanism. The UUV will be secured to the LRS which will engage and lock in the HostSub Payload Tube. Recovery functional hierarchy is displayed in Figure 13.

- 2.0 Recover
  - 2.1 Initiate Recovery Sequence
  - 2.2 Communicate
    - 2.2.1 Establish UUV - LRS - Host Sub Communications Link
    - 2.2.2 Transmit Data between LRS – HOSUB
  - 2.3 Obtain Environmental Information
    - 2.3.1 Determine Host Sub/UUV Depth
    - 2.3.2 Determine Threats (geological/enemy)
    - 2.3.3 Determine Host Sub/UUV Speed
  - 2.4 Determine System Readiness
    - 2.4.1 Receive indications of Host Sub readiness level
    - 2.4.2 Perform Self-Check of LRS
    - 2.4.3 Determine LRS Ready Status
    - 2.4.4 Communicate LRS ready to recover
    - 2.4.5 Receive indication of Host Sub
  - 2.5 Execute Recovery
    - 2.5.1 Extend LRS
    - 2.5.2 Activate Location Device
    - 2.5.3 Grab UUV
    - 2.5.4. Verify UUV Grab
    - 2.5.5 Retract Recover Mechanism
  - 2.6 Secure LRS
    - 2.6.1 Obtain information that retraction is complete
    - 2.6.2 Engage lock
    - 2.6.3 Confirm status of locking mechanism

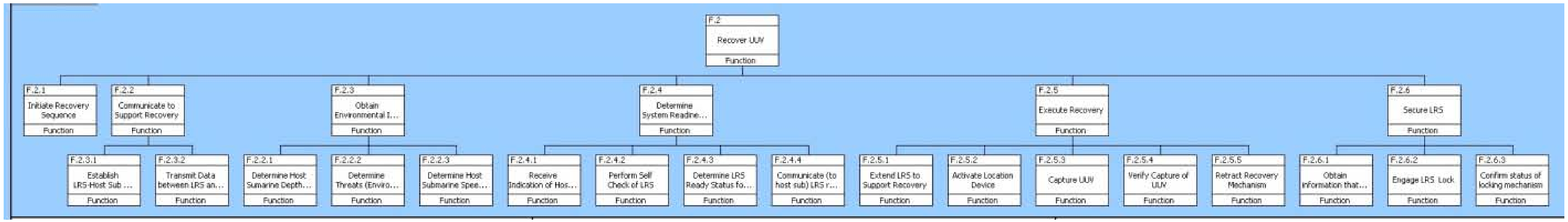


Figure 13 – Recovery Functional Hierarchy

Replenish Functional Hierarchy

Replenish - This function consists of the LRS providing the interface between the UUV and the HostSub to replenish the UUV for the next mission. The LRS has the capability to refuel the UUV and will also be able to establish connections with the HostSub and the UUV to upload/download mission data. Replenish functional hierarchy is displayed in Figure 14.

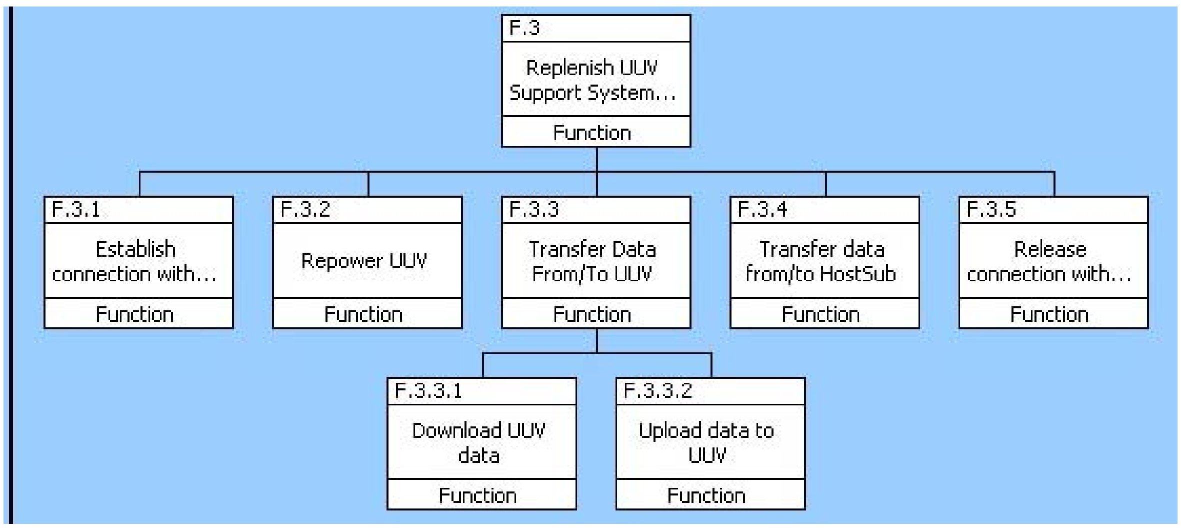


Figure 14 - Replenish Functional Hierarchy

Maintain Functional Hierarchy

Maintain - This function consists of providing diagnostics of the LRS and providing underway repair and maintenance. This function is all inclusive and does not interface with any other system. The Maintain functional hierarchy is displayed in Figure 15.

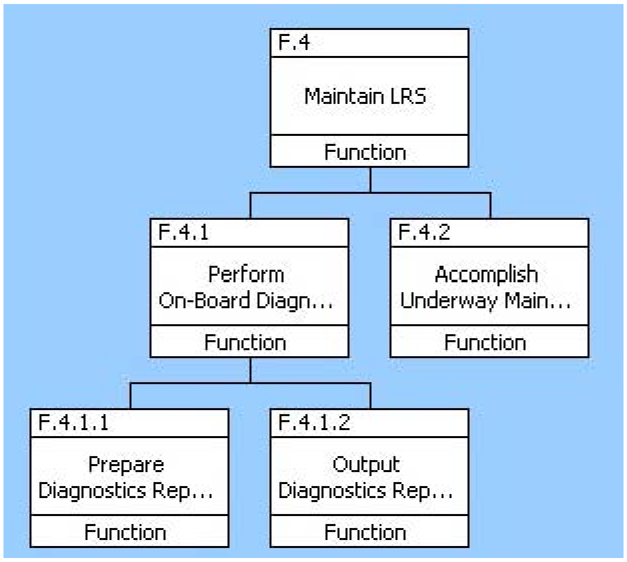


Figure 15 - Maintain Functional Hierarchy

b. Allocation of Functions to Components

Once the functional hierarchy was established, each function was mapped to the corresponding operational activity, performer, component and requirement to provide traceability. This ensured that all attributes were defined and allocated. The IDEF0 graphical output from CORE® was used to describe the allocation of the system functions to its components.

(1) Traceability to System Requirements

A part of tracing the functions to system requirements included mapping the functions to their forms during the decomposition to ensure every function had a component. Figure 16 provides a tabular mapping to identify the system function allocations to the components.

Function	Component Form	Control System Architecture	Support Structure	Launch mechanism	Recovery Mechanism	Stowage System	UUV power and recharging mechanism	RF Communications	Accoustic Commun
F.1.1.	Initiate Launch Sequence			X					
F.1.2	Communicate to Support Launch	X							
F.1.3	Obtain Environmental Launched Based Information	X							
F.1.4	Determine System Readiness	X							
F.1.5.	Execute Launch		X	X					
F.2.1	Initiate Recovery Sequence				X				
F.2.2	Communicate to Support Recovery	X						X	X
F.2.3	Obtain Environmental Information	X							
F.2.4	Determine System Readiness for Recovery	X							
F.2.5	Execute Recovery		X		X			X	X
F.2.6	Secure UUV					X			
F.3.1	Establish connection with UUV/HostSub	X					X		
F.3.2	Transfer data from/to UUV	X							
F.3.3	Transfer data from/to HostSub	X							
F.3.4	Repower UUV						X		
F.3.5	Release connection with UUV/HostSub					X	X		
F.4.1	Perform on-board diagnostics	X	X			X			
F.4.2	Accomplish underway maintenance	X							

Figure 16 – Form vs. Decomposed Functions

c. System Performers and Information Needs

The LRS has one top level system performer, the LRS operator. The LRS operator interfaces with two external systems – the UUV, which is autonomous, and the HostSub operator. The DoDAF OV-2, which is presented in Figure 17, displays the operational nodes with the informational need lines that connect the LRS to the external systems. This information triggers the system to perform the launch and recovery functions. The information passed between these interfaces includes information collected during the mission as well as information to maintain the LRS and determine if it is ready to perform a certain function.

In addition to the top-level interface, to provide a more detailed view of the system, there are two other performers that were mapped. These are the operational nodes, which connect to the HostSub, the US Navy Support Agency and the UUV Equipment Providers. The US Navy Support Agency are where the mission parameters are generated and all information collected during the mission is sent. The UUV equipment providers help troubleshoot the UUV while underway. While maintaining the UUV is outside of the scope of this document, it was recognized since it is a critical attribute in having the LRS mission be successful.

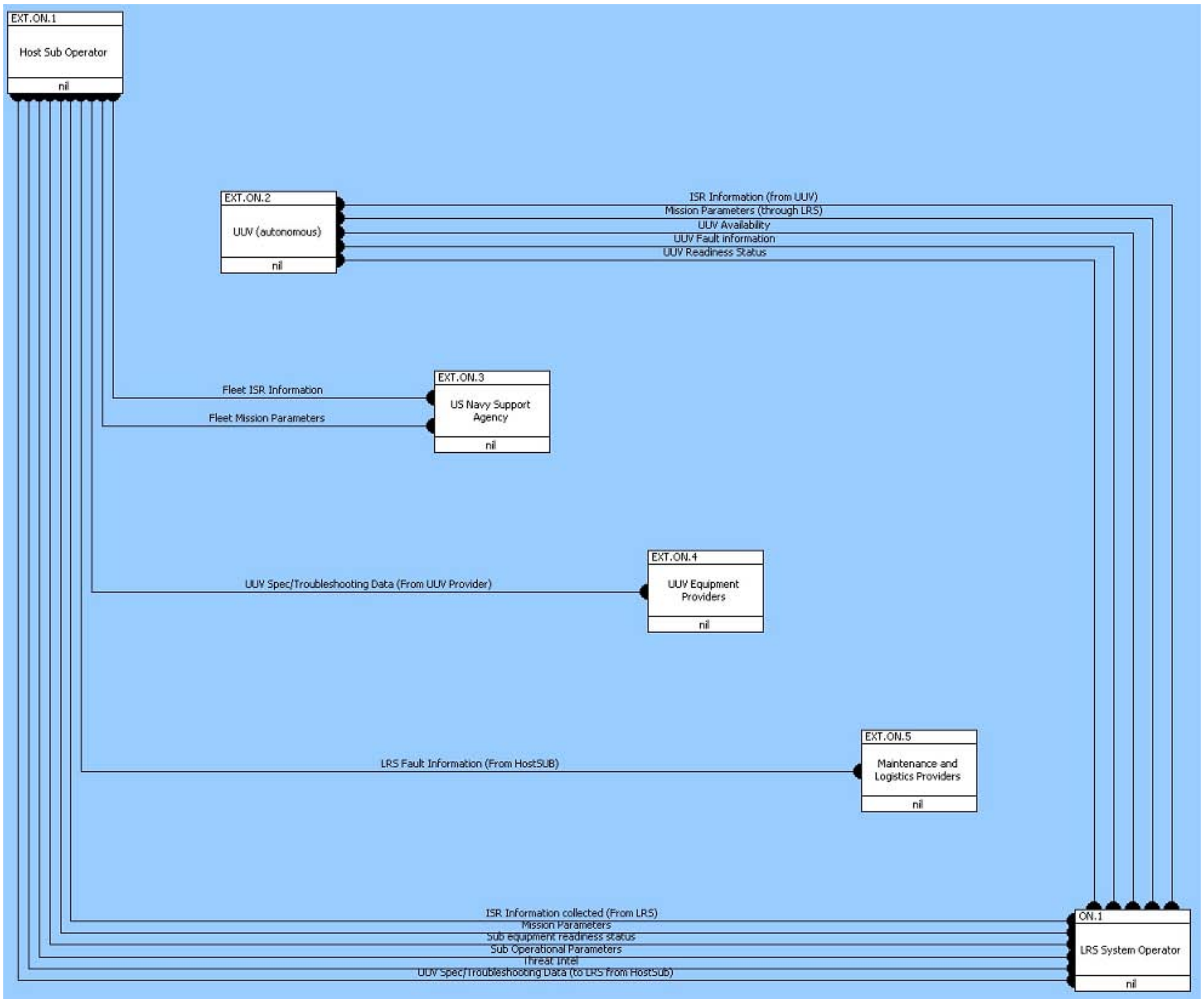


Figure 17 – System Performers and Information Needs

d. Operational Flows

The system operational views were displayed via the extended functional flow block diagram and the IDEF0 views that were generated in CORE®. This view displays the information given in the DoDAF OV-5 and SV-4 views. Both the EFFBD and the IDEF0 give the controls, inputs and output, operational activities and functions; the EFFBD shows the sequence of activities whereas the IDEF0 shows the allocation of operational activities, and input/outputs and controls better than the EFFBD.

Launch IDEF0/EFFBD - The launch EFFBD and IDEF0 are presented in Figure 18 and Figure 19, respectively. The launch function is started by initiating the launch sequence via the launch mechanism that is triggered by the UUV mission objectives report being supplied to the system. Communications, via the control system, will then be established between the LRS and HostSub, and LRS and UUV to upload and download required ISR mission data. The LRS has the capability to obtain environmental information from the HostSub and UUV, including the depth and speed of the submarine and UUV, along with the environmental threats that impact launching the UUV. This data will be used to determine if the LRS is ready to launch. Along with the environmental data, the LRS performs a self-check prior to declaring the LRS is ready to launch the UUV. Finally, the LRS undocks from the payload tube, extends to launch the UUV and then retracts and re-docks into the payload tube. This sequence was conceived to be conducted up to three times consecutively to launch three UUVs during one mission.

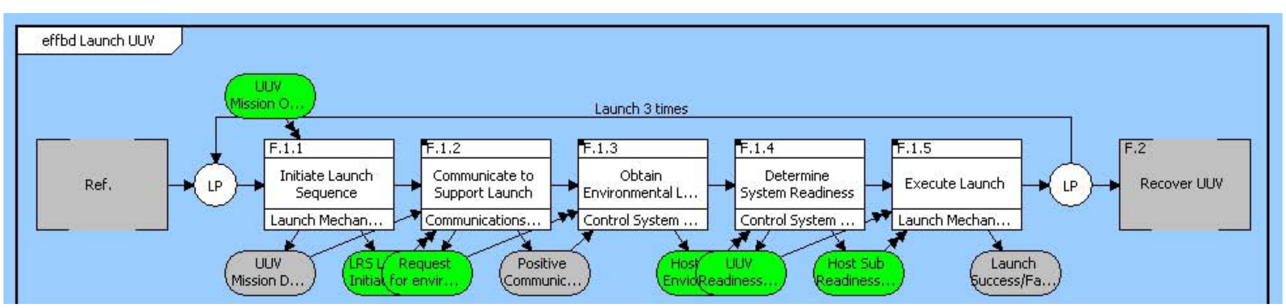


Figure 18 - Launch EFFBD

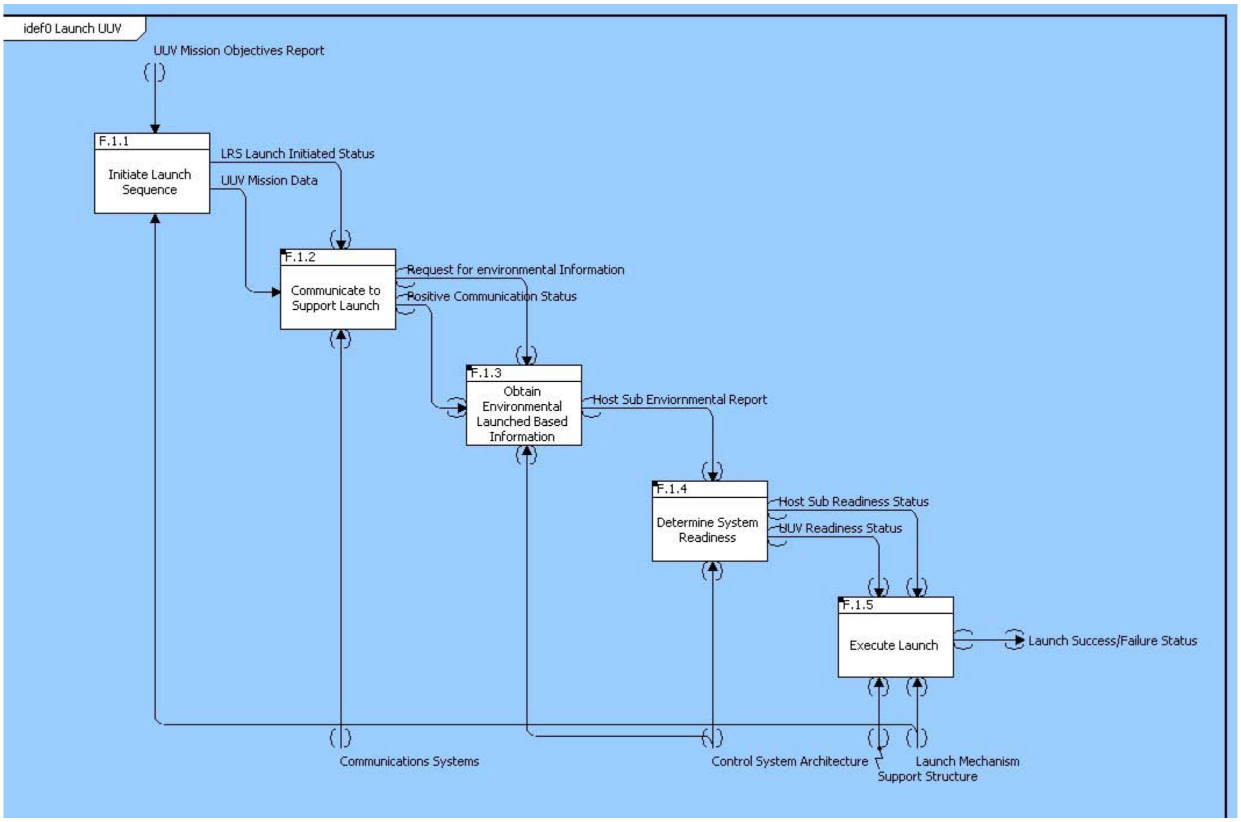


Figure 19 - Launch IDEF 0

Recovery EFFBD/IDEF0 - The recovery function starts with the UUV Mission objective status triggering the start of the recovery sequence and whose EFFBD and IDEF0 are presented in Figure 20 and Figure 21, respectively. Communications, via the control system and RF and acoustic communications, will be established between the LRS/HostSub to obtain environmental information from the HostSub and UUV, including the depth and speed of both the submarine and UUV, along with the environmental threats that would impact launching the UUV. This data will be used to determine if the LRS is ready to support recovery. Along with the environmental data, the LRS performs a self- check prior to declaring the LRS is ready to recover the UUV. Once the system is ready, the LRS will extend and capture the UUV. The UUV will then be secured and locked into the LRS which will then be stowed in the HostSub Payload Tube. Like the launch function, recovery can occur up to three times consecutively.

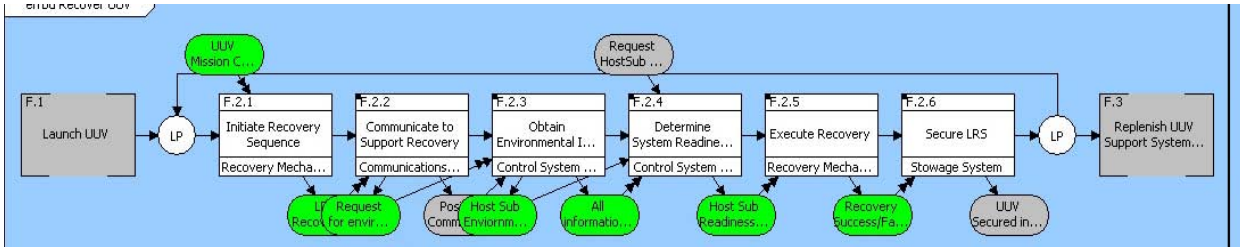


Figure 20 - Recovery EFFBD

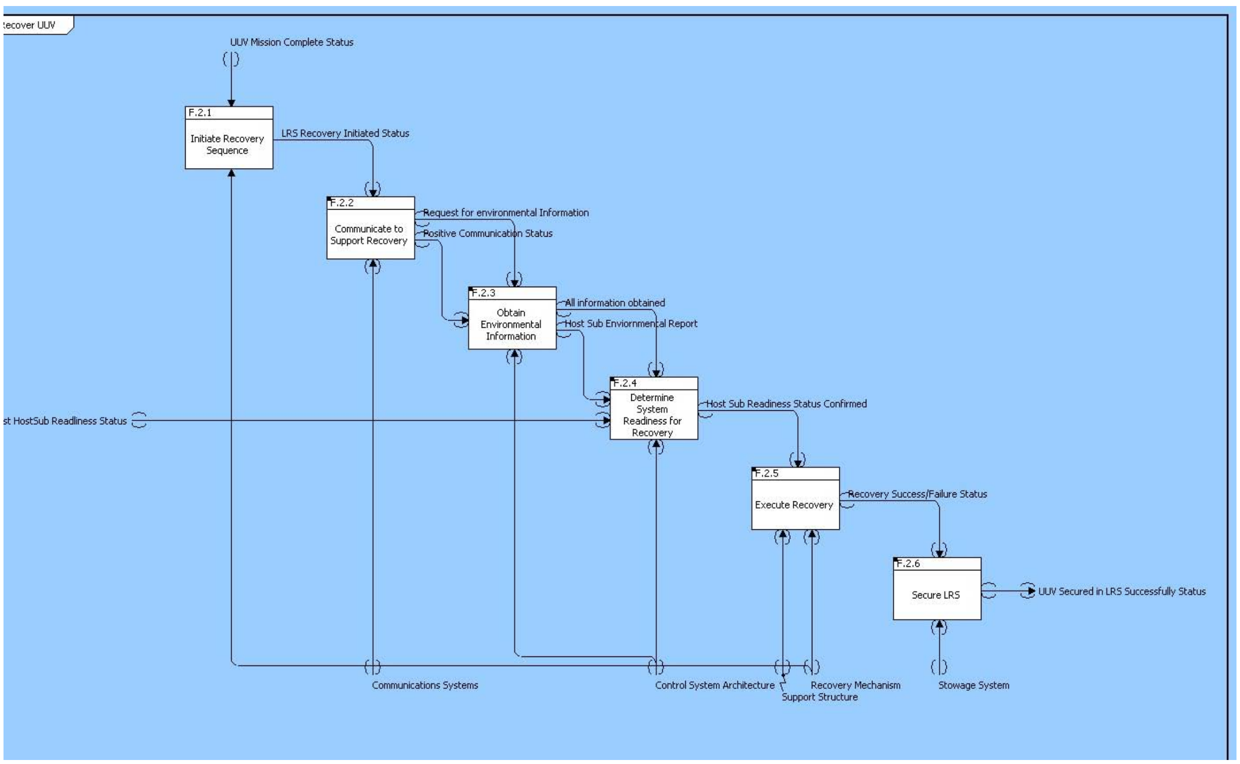


Figure 21 - Recovery IDEF0

Replenish EFFBD/IDEF0 - Once the LRS has recovered the UUV, the UUV replenishment activities will occur. The Replenish EFFBD and IDEF0 are presented in Figure 22 and Figure 23, respectively. This is done by first establishing a connection with both the HostSub and UUV for power and communications. Information will be uploaded or downloaded from the UUV, LRS, and HostSub, along with repowering of the UUV. These events may occur in parallel. Once the system has determined that the UUV is repowered and all information has been downloaded or uploaded, the connection between the UUV, LRS and HostSub will be terminated.

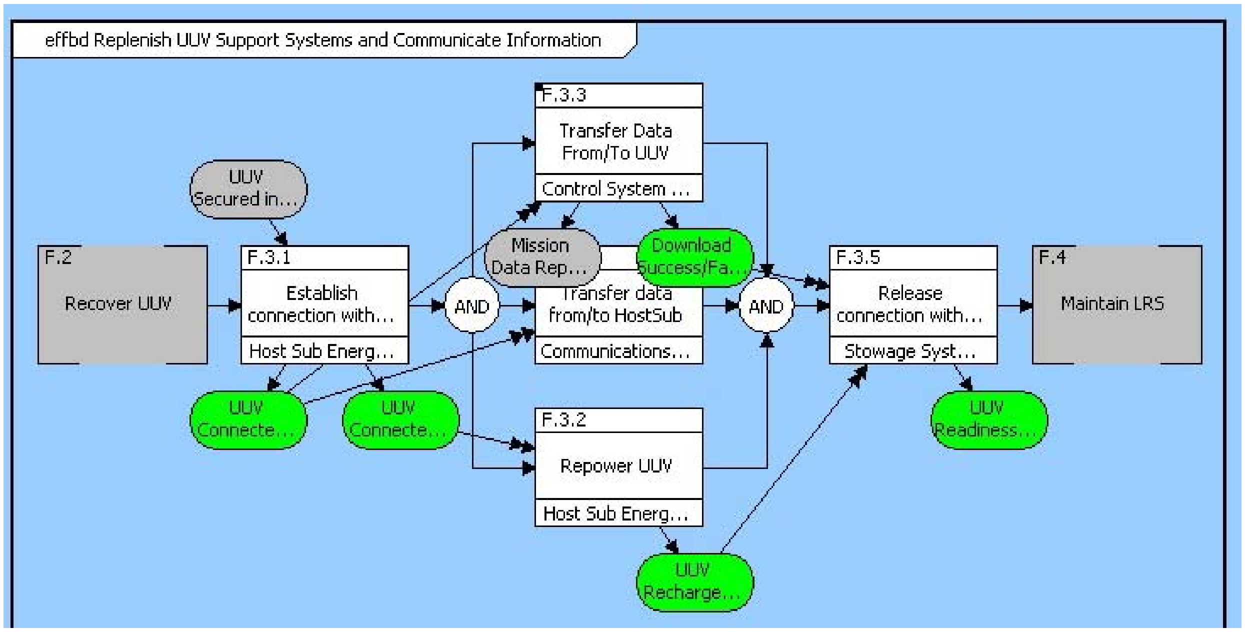


Figure 22 - Replenish EFFBD

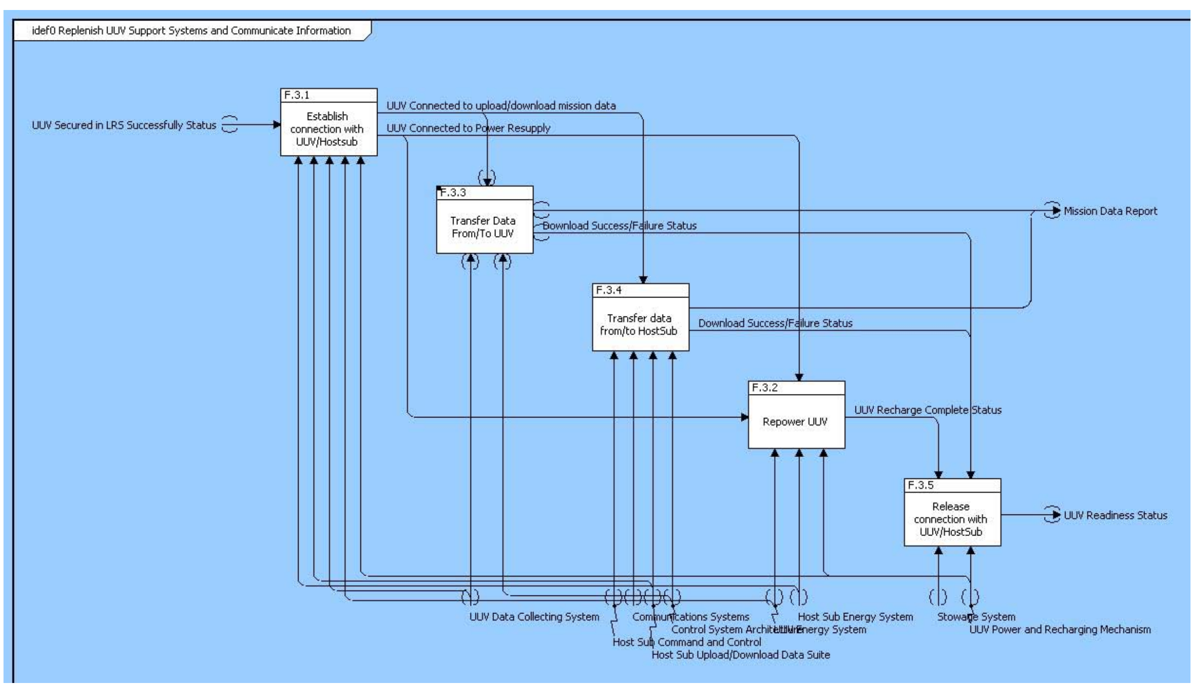


Figure 23 - Replenish IDEF0

Maintain EFFBD/IDEF0 - The last function to be performed is maintain whose EFFBD and IDEF0 are presented in Figure 24 and Figure 25, respectively. The LRS will provide a UUV and LRS Readiness status. The LRS in-service maintenance component, a part of the control system architecture, will perform an on-board diagnostic of the system. If necessary, the system will accomplish maintenance and then be ready for the next mission.

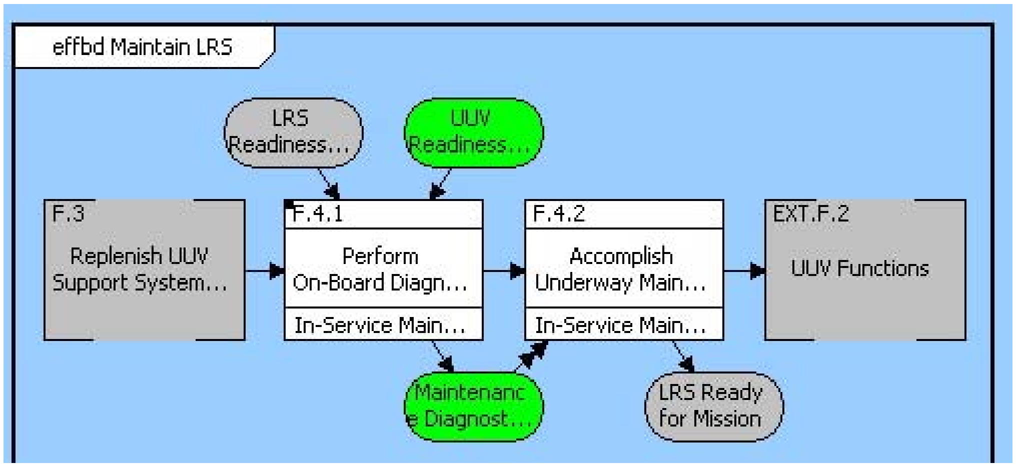


Figure 24 - Maintain EFFBD

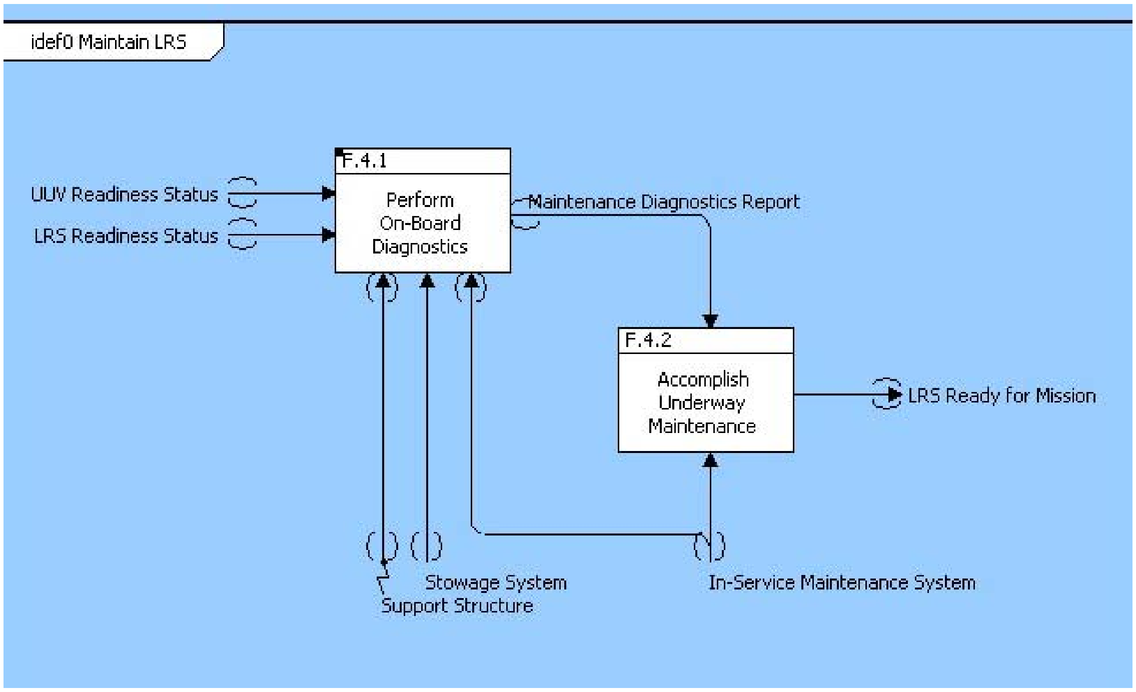


Figure 25 - Maintain IDEF0

C. MISSION ANALYSIS

1. Background

Mission analysis was a process which determined the overall purposes or objectives and capabilities of the system and the circumstances and environment in which the system must operate [SC-21, 1998]. Figure 26 identified the activities and process used to support mission analysis. Mission analysis for this project included analysis of stakeholder needs and coupled boundary conditions, analysis of the specified areas of operations (AO), constraints encountered in the AO, threats to the mission, personnel and/or organizational units needed to support the mission and resources needed to successfully support the mission.

The mission analysis was used to first develop a Concept of Operations (CONOPS) for the UUV/Launch and Recovery Mechanism/Host Submarine Family of Systems. The CONOPS is a high-level viewpoint of how the system operates within its intended environment and was developed using the list of critical tasks, derived from the UNTL. From this CONOPS, specific AOs, constraints and threats were considered to develop several important mission scenarios that would be supported.

These mission scenarios assessed the functionality of the proposed system concepts. The functionality was traced upward to ensure that the needs of the stakeholders met the plausible missions of the system and traced downward to measure performance of physical concepts against each other. With these mission scenarios, the project team analyzed the operational environment and boundaries of the system and identified potential interactions with external entities, which might have been otherwise missed, and created performance requirements for the system.

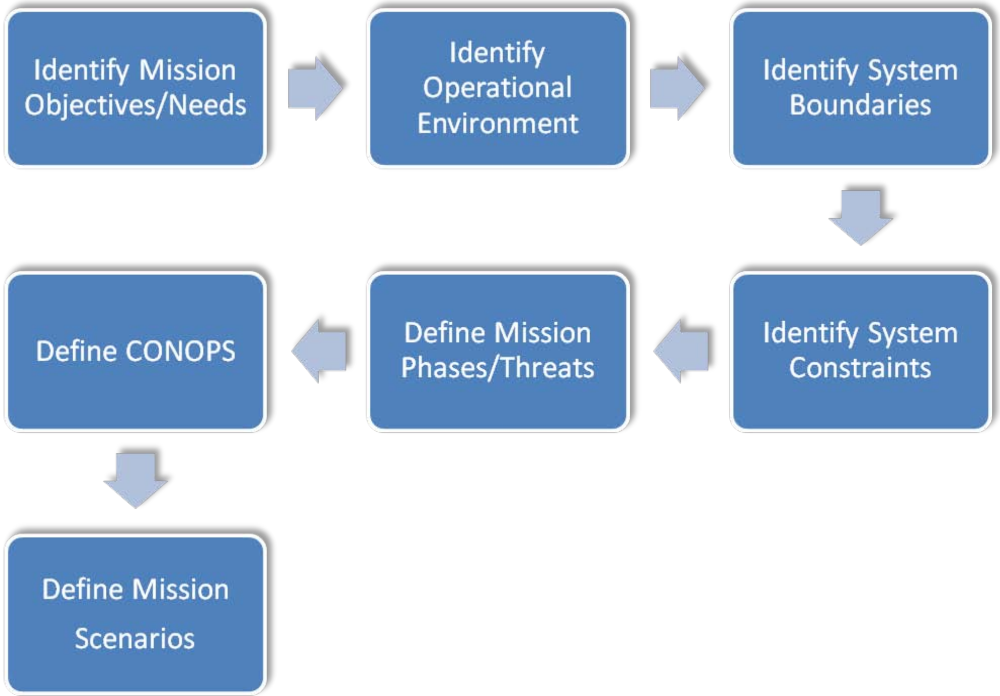


Figure 26 – Mission Analysis Process Diagram [SC-21, 1998]

2. External Boundary Conditions

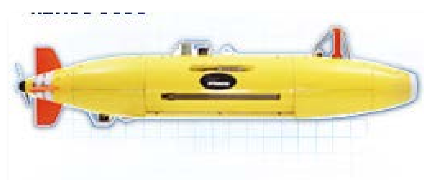
a. UUV System

There are numerous large UUVs built for ISR-type operations by different vendors. To support the success of this project and define the interfaces necessary to support integration, a "standard" Large Vehicle Class UUV system was defined. The "standard" Large Vehicle Class UUV captured most, if not all, of the major performance requirements and functions inherent to currently conceived large UUV systems. The following sources were used to capture the major requirements and functions:

- Overarching system design requirements specified in the UUV Road Map Report issued by NAVSEA 073R, Director of Undersea Technology. [SEA 073R, 2008]
- The Survey of Large Unmanned Maritime Vehicles prepared by Johns Hopkins Applied Physics Laboratory [Hopkins, 2010]
- The identified mission requirements based on the Stake Holder Goals concerning CNO Requirements for a 30 Day Mission in Seven Years from "Inside The Navy" [Inside The Navy, 2010]
- The technology requirements based on the information specified in Department of Defense, Militarily Critical Technologies List Section 13: Marine Systems, Technology, January 2009, Under Secretary of Defense, Acquisition, Technology and Logistics Pentagon. [MCTL, 2009, Section 13]
- The review of ASTMs established to define common parameters for UUV development. [ASTM F2594-07, ASTM F2545-07, ASTM F2541-06, ASTM F2595-07]

- Consideration of other technical factors and design requirement, including shock, safety and commonality.

Following examination of the source documentation, several existing large UUVs designed for specific use on ISR-type missions, including Bluefin Robotics Corporation BPAUV, Sea Otter MK II and REMUS 6000 (see Figure 27) were evaluated for common features and functions. Through this analysis and determination of threshold and objective requirements for the existing systems as well as review of standards and possible developments for "near-future" systems, a "standard" Large Vehicle Class UUV were defined. Table 4 provides the detailed attributes of the "standard" Large Vehicle Class UUV utilized for this project.



Bluefin BPUAV [Keller, 2008] **REMUS 6000 UUV [Kongsberg, 2008]**

SEA Otter MK II UUV [AUVAC, 2008]

Figure 27 – Typical Large Class Vehicle UUVs

Table 4 – Parameters for "Standard" Large Vehicle UUV

Attribute	Low-End/ Conventional	High-End/ Cutting Edge	"Standard" Large Vehicle Class UUV Capability
Length	12.6 FT	28.5 FT	28.5 FT
Outside Diameter	28 IN	66 IN	66 IN
Body Shape	Round	Hydroplane	Multiple
Weight (Dry)	2000 LBM	17600 LBM	20000 LBM
Operating Depth	200 FT	1000 FT	1000 FT
Hovering Control	None	Variable Ballast Tanks	Variable Ballast Tanks
Speed	0-4 Knots	2-12 Knots	2-12 Knots
Range	22 Hrs @ 4 Knots	1600 Nm @ 3.6 Knots	2800 Nm @ 4 Knots
Propulsion	Dual Rotating Props	Ducted Pump Jet w/ 5 Rotating Blades	Ducted Pump Jet w/ 5 Rotating Blades
Power/Capacity	Silver-Zinc Battery / 10kWh	Li-Ion Rechargeable Battery / 360kWh	Rechargeable Battery / 500kWh
RF Communications	None	Freeay LOS-RF, Inmarsat Sailor-250, Iridium Satellite, Inmarsat Sailor 250 Satellite	Freeay LOS-RF, Inmarsat Sailor-250, Iridium Satellite, Inmarsat Sailor 250 Satellite
Acoustic Communications	None	Custom WHOI, emergency Comms are Edge Tech Acoustic Transponders	Custom WHOI, emergency Comms are Edge Tech Acoustic Transponders
UUV Operational Availability (Ao)	0.84	0.95	0.90
UUV Mission Duration	20 Hrs	18 Days	30 Days (Goal)
UUV Navigation System Accuracy	+/- 0.5%	+/- 0.3%	+/- 0.5%

b. Host Submarine System

The host platform for this project was the USS VIRGINIA Class (VA) Block III attack submarines. The USS VIRGINIA (SSN 774) Class of submarines were designed for both open-ocean and littoral missions. Their design is a more economical alternative to the Cold War era

USS SEAWOLF Class (SSN 21) attack submarines, and will replace the aging USS LOS ANGELES Class (SSN 688) submarines. This class of submarine, designed by Electric Boat Corporation, is being jointly constructed by Northrop Grumman Newport News (NGNN) in Virginia (now known as Huntington Ingalls Industries) and Electric Boat (EB) in Connecticut.

VA Block I and II submarines are equipped with a Vertical Launch System (VLS) consisting of twelve individual tubes located in the forward section of the submarine. This was the SSN 688 Class attack submarine VLS configuration. Starting in 2002, the Navy converted four USS OHIO (SSBN 726) Class submarines to SSGNs. These conversions consisted of modifying the existing 88-inch diameter ballistic missile tubes to accommodate up to twenty-two (22) Multiple All-Up Round Canisters (MAC) which provide the capability to store and launch seven Tomahawk cruise missiles while reserving the remaining two ballistic missile tubes for Special Operating Forces (SOF) support or other essential missions. The successful conversion of these large diameter ballistic missile tubes to MACs and other mission uses provided the Navy justification to develop this concept on the VA submarines in the Block III hulls. VA Block III submarines will be equipped with two larger diameter tubes known as Virginia Payload Tubes (VPT) in lieu of the twelve (12) individual VLS tubes found on Block's I and II. Each payload tube can accommodate a MAC, used for Tomahawk support, or can be configured to support SOF and/or UUV missions. Figure 28 shows the general configuration envisioned for Block III implementation of the VPT concept.

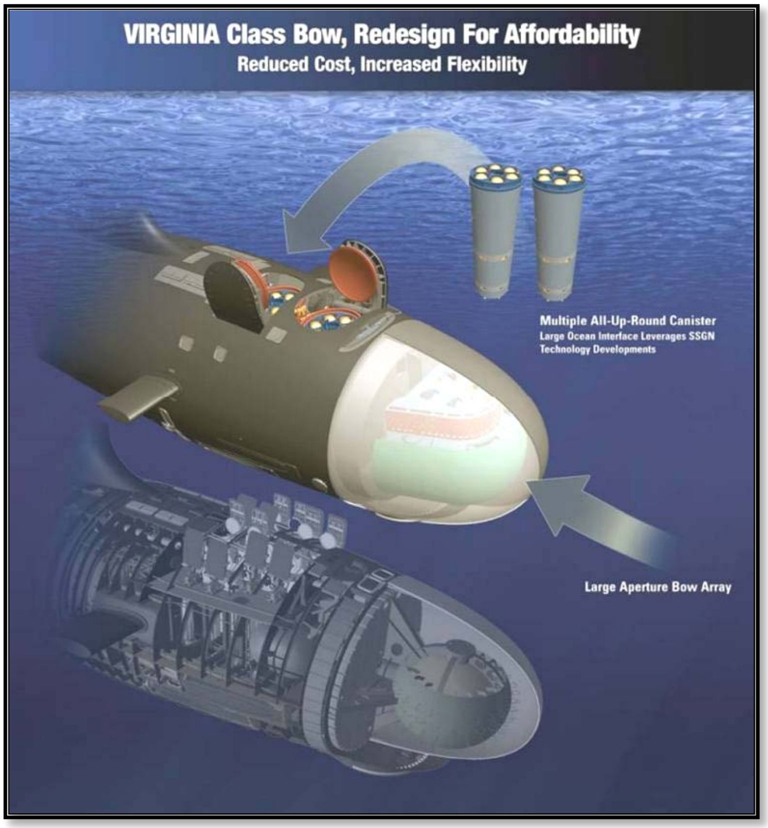


Figure 28 – Virginia Class Block III Concept with Block I / II shown in Shadow [Defense Daily, 2008]

3. Constraints

A constraint is a restriction, regulation, or checks that prevents, limits or dictates the actions of the system within proscribed bounds. Through analysis of literature, needs and operational concepts, five (5) main categories of constraints were identified: Natural, Physical, Policy, Operational and Man-Made.

a. Natural Constraints

Ocean Environment - VA Class Block III submarine launch, communication and recovery of Large Vehicle Class UUVs would be subject to weather and sea state conditions. In the worst sea conditions, actual underwater launch and recovery may prove impossible; however, even minor conditions might have an adverse impact on system reliability and mechanism performance. Rough sea states or strong currents could interfere with the transmission and reception of data to/from the UUV and submarine or with the navigation capabilities necessary to close and recover the UUV with the mechanism. Sea state and water temperatures could limit replenishment and recovery efforts, especially if manned operations are required. The submarine might be limited in its ability to come to periscope depth to transmit data from the UUV based on weather conditions. Warm Water Operations (defined as greater than 90°F) have been known to impact equipment reliability, and may contribute to contamination and fouling. Corrosion of materials exposed to seawater must also be considered.

Topography – The submarine would launch and recover UUVs near hostile coastlines. Water depth at the coastline may affect the ability for the host submarine to approach the coastline. Currents may be stronger in the intended operational environment than at deep-sea operations. Due to limited depths, underwater mountains and features may affect communications and maneuvering of the equipment. Shallow operations and extended periods of hovering or on-site operations could result in exposure to more marine life forms and increased biological fouling of equipment.

b. Physical Constraints

Vehicle Characteristics – The large diameter, weight and shape of current and future Large Vehicle Class UUVs would tax the host submarine and the capabilities of a launch and recovery system. Future iterations would expect larger power supplies for UUVs to support persistent-ISR missions. The submarine must have the capability to recharge the UUV power supply. Additionally, multiple launch capabilities from a single host submarine require consideration for storage capabilities within submarine launcher tubes. To offset weight additions, power impacts and shock considerations, lightweight materials with equal strengths of structural steels must be considered in the design of the supporting structure. Such materials must successfully trade off cost considerations with performance considerations.

Communications - The submarine communications suites have the capability to interact with the sensor suites on the UUV, through an interface with the LRS, and retransmit data via Ultra High Frequency (UHF) satellite relay and line of sight (LOS) links to maintain command, control, and sensor data communication paths. Bandwidth compression would be applied to sensor data to maximize area coverage and data throughput. However, bandwidth capabilities might be taxed as more and more data transmission is required, requiring additional and costly power sources. Furthermore, timeliness of the transmitted signals may create problems. The support command has the responsibility to integrate the data transmitted from the submarine received from the UUV into the theater Defense Information Infrastructure (DII) to provide timely dissemination of collected intelligence to the requesting customer.

c. Policy Constraints

Tasking Order - The means for implementing persistent-ISR missions for a VA Class submarine was assumed to be the tasking order. The Tasking Order would include the employment plan. The Fleet Commander tasks the submarine to launch UUVs to accomplish specific missions and to provide data with sufficient detail to execute persistent-ISR missions. The support element must be capable of generating the mission plan within the time constraints of the tasking order cycle. The Operational Commander issues the tasking order, which is valid for a specific period. The Operational Commander's Intelligence Division would determine that the submarine launched UUV would conduct the mission based on coverage requirements, communications connectivity with supported units, and survivability considerations. The tasking order planning, coordination and execution is a continuous process, which may cross several tasking order cycles. The effective and efficient use of submarine launched UUVs for persistent-ISR missions requires coordination between the intelligence and operational commanders and multi-service/coalition liaisons within the command. During mission execution, the commander(s) support by the data collected by the UUV might request changes in coverage areas or times. These changes must be coordinated through the submarine immediate superior in command (ISIC), and Fleet Commander.

Water-space Management - The Fleet commander is responsible for the safe operation of the platforms under his control.   Operating procedures with adequate margins of safety for naval vessels in high traffic areas need to be developed for current and future UUV operations Likewise, the VA Class Block III submarine commander is responsible for the safe operation of his ship, the interfacing launch/recovery mechanism and the UUVs. Policies must seamlessly integrate with over-arching policies and allow control of multiple UUVs, possibly launched and recovered from platforms other than the on-station host submarine.

d. Operational Constraints

Safe Operations – A system of redundant communications will be required to ensure the submarine can adequately navigate with and monitor UUV actions in close quarters. Considerations must be made for a UUV vehicle, which cannot make it back to a pre-programmed recovery point and must be abandoned for future recovery or destroyed either in a high traffic sea-lane or in enemy waters. The LRS must consider speed and flexibility of recovery, both features which will likely result in increased costs.

Force Structure - In general, the U.S. Navy requires multiple VA Class submarines with the capability to launch, control and recover large UUVs for persistent-ISR missions, be available in the operational area to support training and exercises. The UUV’s coverage constraints are dictated by power supply constraints, transit distances to the operational area and the ability to recover UUVs once deployed.

Manpower - As the VA Class Block III Submarines are certified for unrestricted operations, the Commander Submarine Forces Command must consider training and equipping the force for operations and maintenance of the LRS.

Physical Security - Submarine and UUV protection requirements are based on the location of the submarine, the tasked mission, and the Department of the Navy's physical and operational security programs. Commander Fleet Forces Command, in conjunction with the Office of Naval Intelligence will need to develop and implement any additional physical security requirements for the VA Class Block III submarines when UUVS are loaded with the appropriate support systems installed. The standards will identify the security priorities and establish requirements for security forces and equipment aids.

Information Security - These requirements include addressing anti-tamper and force protection requirements with both received and distributed information. The information that needs to be protected will include the mission profile, and associated operational orders and constraint, and the data collected during the ISR Missions.

Operational Security - Operational Security requirements are designed to prevent tampering with critical information. In this case, it includes the control systems architecture and the communications system, both of which must be maintained secure. This is done by the use of controlled work packages for maintenance and configuration changes, as well as encrypted secure communications. It is anticipated that the existing radio and acoustic communications systems shall meet these requirements.

e. Man-Made Constraints

Enemy Actions - Communications systems were engineered to minimize susceptibility to jamming and interception. Dissemination of UUV collected intelligence sent to the submarine is made through direct downlinks to national, theater intelligence centers, and exploitation systems. As the proposed system acts as a bridge between the UUV and the host submarine, considerations must be made to limit jamming and signal disruption by enemy forces and/or spurious signals. Additionally, components used to launch and recover the UUVs must consider minimizing radiated noise and/or signature to minimize detection by enemy threats.

Noise/Information Pollution - Operation in littoral areas are known to be extremely noisy environments and pose issues not only to detection, but also to collecting information on targets and disseminating information. Sensor design and power requirements demand larger vehicles to meet persistent-ISR capabilities. Override controls potentially necessary to support maneuvering operations of UUVs at launch and recovery must be robust enough to overcome background noise and interference.

4. Mission Phases and Threats

There are four (4) distinct mission phases for the LRS: Pre-Mission (includes transport, loading and securing of the UUV and launch/recovery mechanism into the host submarine), Launch (includes download of mission parameters), Recovery (including stowage of UUV into launch/recovery mechanism and securing of equipment) and Post-Mission (including download of ISR data, and in-service maintenance and troubleshooting/diagnostics). Each phase of the mission face a certain level of risk associated with common and/or unique threats to that phase.

A threat is a plausible risk that could inflict harm on either personnel and/or equipment. Threats might be the result of natural events, accidents or intentional acts meant to cause harm.

Plausible threats to the family of systems (UUV, host submarine and launch/recovery system) in each phase of the mission were examined as follows:

Pre-Mission – Threats to equipment and personnel include accidental damage during the loading operations and/or transport. The Large Vehicle Class UUVs can weigh as much as 20,000 lbs and the LRS is likely to weigh up to 100,000 lbs. As such, crane operations will be required to support loading into the launcher tubes. Tight clearances and typical risks associate with heavy lifting operations can lead to damage to the LRS, UUV and/or the host submarine. Of critical concern, is the damage than cannot be visually detected, such as internal damage to computer systems, communication systems or any equipment with internal components. A robust testing strategy and pre-mission inspection capabilities would aid in evaluation of system capabilities prior to deployment of the loaded system.

Launch – A rapid and silent launch will be critical to avoid submarine and/or UUV detection by enemy forces. Both the submarine and the UUV are vulnerable to threats during launch given its submerged operating envelope. Operational concepts identified that the submarine would launch UUVs at shallow depths (no less than periscope depth). At shallow depths, the threat to the submarine is broad, from detection by enemy sonar and radars to visual detection, leading to torpedo and missile attack. Rapid launch would constrain deployment times of LRS components, requiring robust, flexible and technologically advanced equipment to prevent damage from accidents and sea conditions at shallow depths. Additionally, the communications between the submarine and the UUV via the interface of the LRS during the launch phase must be suitable to prevent deployment of a UUV with incomplete or inaccurate mission data. Although upload of information and mission parameters would likely feedback erroneous information to operators, problem with the data interfaces could produce false readings. Furthermore, positioning of host submarine and LRS equipment will be vital to ensuring impact accidents do not occur. Sensor feedback mechanisms must be robust and redundant to the necessary level of reliability.

Recovery – Similar to the launch phase, rapid and silent recoveries of the UUVs would be critical to avoid detection. As discussed before, the submarine would recover the UUV at shallow depths, where enemy risks of detection and/or harm are significant. Recoveries would likely pose a more significant risk of accident as the UUV is affected by ocean movement currents/tides and may not be directly attached to the LRS as it is during launch. Clear and real-time operator feedback would be essential to prevent the UUV from damaging itself, the host submarine and the LRS from accidental impacts. In addition, recovery encompasses secure stowage of the LRS as well as the UUV itself. Vibrations must be minimized to avoid radiated noise and equipment damage due to shock and other lesser differential forces. Equipment must minimize slop between components and false readings concerning interface between the internal and external system boundaries. Finally, recovery might require the use of an active acoustic communication feature (such as a sonar "pinger") that locates the UUV and provides a "homing" feature. Any such acoustic communications feature could lead to detection by enemy forces and compromise of the UUV and host submarine assets if not judiciously and sporadically deployed.

Post-Mission – Interfaces between the UUV and the host platform must be robust and compatible to support a rapid transition of the ISR data to the intelligence network. Systems where communications flow through a wireless means may be more rapid than a hardware solution, but might also be more susceptible to compromise. Threats could include active and passive detection capabilities by enemies and well as interception, requiring a level of encryption and security that may further inhibit timely information transfer. Post-mission activities were expected to include diagnostic and trouble-shooting activities to prepare the family of systems for subsequent missions. Such activities must provide a technically sound and, at times, a cautious approach to prevent hardware/software damage to system components. Limits to underway repairs must be recognized and logistics must support on-board equipment or redundant components that maximize times between mission failures. In addition to trouble-shooting and diagnostics, replenishment of the UUV through the LRS, primarily re-charging of the UUV power source, will occur. Accidents such as an electrical fire, power surge or an interface capability issue could damage the equipment or delay subsequent missions.

5. Concept of Operations

The Large Vehicle Class UUV LRS was the interface system between a FOS, brought together to support persistent-ISR underwater missions such as intelligence collection, target detection and undersea mapping. The LRS will be installed into a VA Class Block III submarine VPT dockside prior to submarine deployment. A single or multiple Large Vehicle Class UUVs will likewise be loaded onto the submarine prior to submarine deployment and physical integration between the host submarine and the UUVs will be accomplished through the LRS.

During host submarine deployment to an area of operations, mission information will be received and up-loaded to the UUV(s). UUV launch would occur at a safe standoff position and the UUV would transit from this location to the area of interest. Minimal operator control of the UUV would be expected to support launch. The UUV would operate autonomously and clandestinely within a given range and mission duration. Mission updates and data transmissions would occur, as necessary, via pre-located communication buoys, dropped by ships or aircraft within the area of operations. Future system upgrades might implement the capability for direct host submarine contact with the remote UUV. If host submarine communications would require interaction between the submarine and the UUV, it would be through an upgraded LRS.

The Launch and Recovery Mechanism Command, Control and Intelligence (C2I) component provided the primary interface for the UUV vehicle to the host submarine. It was expected to be a commercial-off-the-shelf (COTS) open architecture C2I system, designed to maintain positive control of the LRS to prevent operational mishaps such as vehicle casualties, collision or sensitive technology being compromised by foreign entities [Unmanned System Safety Guide for DoD Acquisition Systems, 27 June 2007].

Following completion of the mission, the UUV would return to a rendezvous point and transmit information necessary to support acquisition by the host submarine. The host submarine would recover the UUV, safely stow the vehicle on board and, if necessary transit to a safe zone. Some operator control of the UUV was anticipated to support recovery operations. The interface device would support download of data from the UUV to the host submarine and replenishment of the UUV, including re-charging of the power supply, changes to the software package and routine software testing and maintenance actions. Under certain conditions, the LRS may allow personnel or diver access to the UUV to support underway and/or payload changes. The LRS was expected to support multiple launches and recoveries during a single deployment cycle. A graphical illustration of the operational overview (OV-1) and an expanded view that shows the integration of the UUV LRS with the external boundaries is depicted in Figure 29.

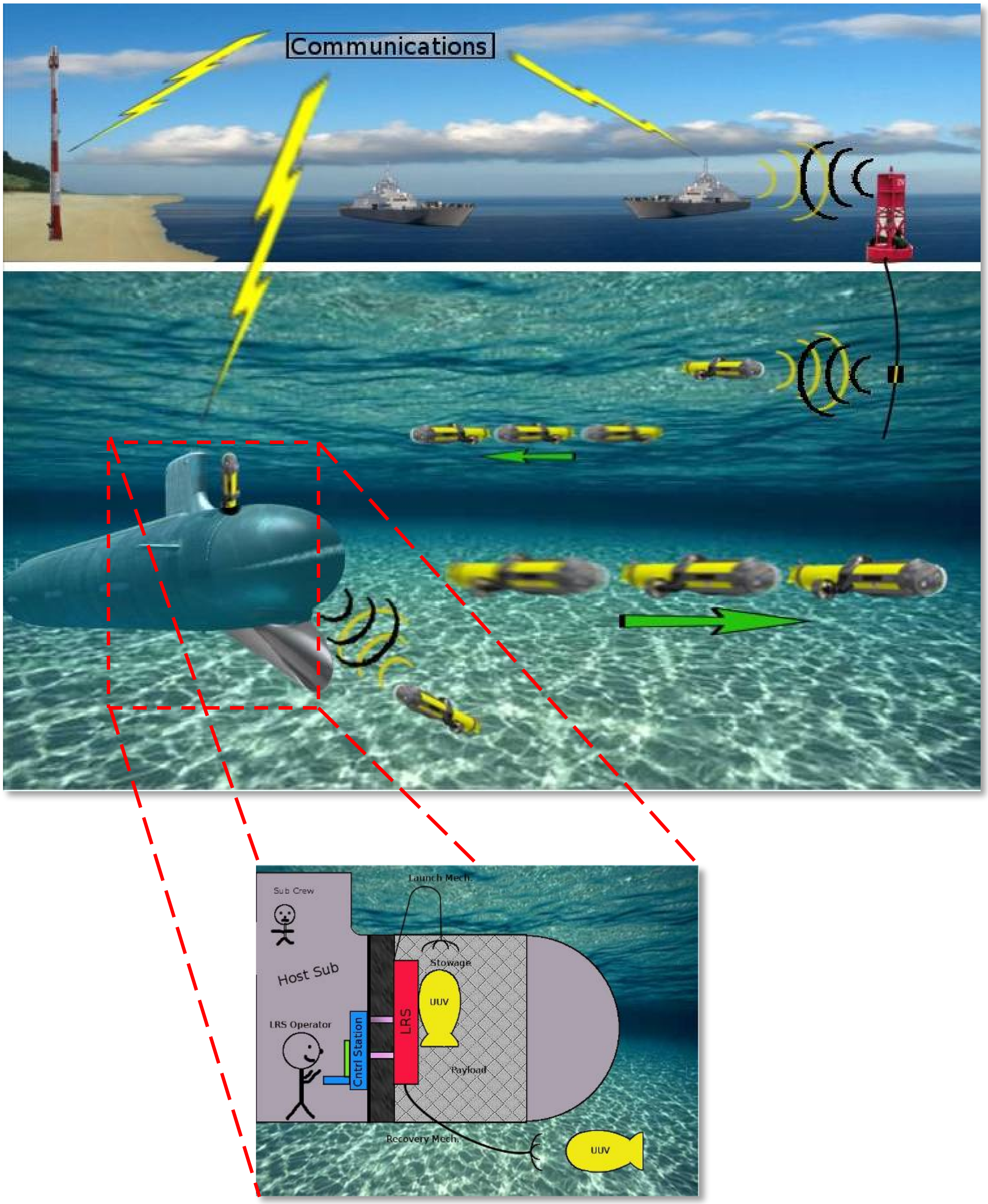


Figure 29 – System Operational Overview (OV-1)

6. Mission Scenarios

a. Launch and Recovery Performance

In a mission scenario, which demonstrated performance of LRS, the host submarine would launch multiple Large Vehicle Class UUVs (up to 3) in succession while avoiding detection and sea traffic. After a set mission period, the submarine would then re-establish contact with the UUVs and return to rendezvous point where recovery and stowage of the UUVs would take place. Light, average and severe weather conditions typical for a well-travelled AO would be used to assess different version of this scenario. Measures of success would be rapid launch and recovery of UUVs with limited mishaps, system availability and factors related to detection of UUV/submarine during launch.

b. Disabled Vehicles

This mission scenario proposed assessment of retrieval capabilities for Large Vehicle Class UUVs with various levels of functionality. In this scenario, the host submarine would arrive a rendezvous point and attempt to establish communications with UUVs in various stages of functionality (25%, 50%, 75% and 100%). Returning UUVs communicate with host ship via the LRS and begin the retrieval process. Measures of success would be determined by timely and mishap-free retrieval of UUVs with various capability limitations (communication systems, propulsion, hovering, and/or structural damage).

c. Replenishment Performance

This mission scenario proposed an assessment of replenishment of UUV systems while stowed in the LRS. It will measure the amount of time necessary to recharge the battery system under various conditions and assess the communications and interfaces between the UUV and host submarine to transfer data. Additionally, the underway scenario would evaluate the security of the system, both electronically and mechanically, when stowed. Electronic security can be analyzed via complexity of security issues and how data transfer would occur. Mechanical security is an assessment of radiated noise caused by the stowed systems and resistance to vibration and shock loading. Measures of success would include the timeliness of replenishment and data transfer and a qualitative assessment of noise created by a system.

III. FUNCTIONAL ANALYSIS AND VERIFICATION

A. ALLOCATE SYSTEM FUNCTIONS AND DEFINE CONCEPTS

1. Background

Following definition of stakeholder requirements, functional architecture and mission/operational requirements, the next step was to determine conceptual design alternatives for the system. The team decomposed the stakeholder weighted needs into performance measurements, functions and component concepts that reflect the values of the project stakeholders. The result developed the baseline requirement products and conceptual design alternatives that were used to accomplish comparisons and analysis in follow-on phases of the project.

2. Establish System Component Concepts

To identify technologies and component concepts that could be integrated and make up the recommended design of the system, the team first sought to establish and weigh system performance capabilities and the system-level functional hierarchy. Based on the stakeholder requirements and using the UNTL, literature and the "standard" Large Vehicle Class UUV description as starting points, objectives were conceived to meet the requirements and metrics were proposed as measurements to assess the satisfactory performance of the objectives. Next, using QFD models, system performance, function and conceptual components were ranked against the weighted stakeholder requirements.

a. Performance Requirements and Metrics

The Requirements Analysis established the design criteria to produce a preferred system, which met customer expectations. Initial steps served to develop qualitative aspects of the system, represented by the customer requirements or "what" the customer wants from the system. However, to successfully evaluate competing concepts, quantitative aspects of system performance must be applied to each requirement. As such, evaluation measures were established for each of the stakeholder requirements and are displayed in Table **5**.

For each requirement, one or several "objectives" were established. Objectives represented a means of measuring the intent of a customer requirement. For instance, stakeholder interviews determined that the system must accommodate large UUV re-chargeable power sources to support extended persistent-ISR UUV missions. However, the definition of "accommodate" in this context left multiple integration issues open for interpretation. Accommodate represented spatial considerations (size, volume) but also represented strength considerations (weight, structural material properties) and support considerations (energy supply, transmission of energy). Objectives were developed to represent the accommodation characteristics in measurable ways, identified as Technical Performance Measures (TPM). Evaluations of these measures were expressed in terms of ascending or descending values. Assignment of actual values for performance objectives occurred as part of concept development and modeling & simulating the different conceptual design alternatives.

Table 5 – System Performance Objectives

Requirement	Objective	Technical Performance Measure (and Evaluation)
Host Submarine Safety	Decrease Mishaps	Percent of missions that result in damage to sub (lower is better)
	Resist Shock Damage	Percent of shock events that result in damage to Grade A equipment (lower is better)
	Decrease Detection	Minutes of avoiding detection by enemy in operational area (higher is better)
Accommodate Large Power Needs	Maximize Payload Space Envelope	CUIN of payload capacity (higher is better)
	Decrease Load on Submarine Power Supply	Amps required to re-charge UUV (efficiency of charging process) (lower is better)
	Maximize Power Transmission Transfer (both in the submarine and while deployed)	Hours to re-charge UUV (lower is better)
Operational Performance	Decrease Launch Time	Launch time in minutes (Tube flooded to UUV underway) (lower is better)
	Decrease Recovery Time	Recovery time in minutes (Local UUV control obtained to UUV stowed) (lower is better)
	Maximize Potential Operating Environments	Launch and recovery capability in Sea State Number (higher is better)
Resist Shock and Noise	(Subset of Host Submarine Safety Objectives)	
Reliability	Maximize System Time to Failure	Months of satisfactory performance before failure (higher is better)
Affordability	Reduce Acquisition Costs	Current Year Dollars (lower is better)
	Reduce Life-cycle Costs	Current Year Dollars (lower is better)
Flexibility	Supports Multiple UUV payloads	Number of significantly different UUV designs supported (higher is better)
	Supports Multiple UUV payloads	Time to modify system (pier side) to accommodate significantly different UUV designs (lower)
Weight Control	Reduce Impact on Submarine Stability	System Center of Gravity (CG) in inches (lower is better)
	Reduce Impact on Submarine Weight margin	System weight in pounds (lower is better)
Maintainability (Supportability) At-Sea	Decrease Turn-around	Time between successful re-launch of UUV at-sea (lower)

Table 5 – System Performance Objectives (Continued)

Requirement	Objective	Technical Performance Measure (and Evaluation)
Multiple Launch Capabilities	Increase Missions	Number of controlled UUVs in operational area simultaneously (higher is better)
Communications	Increase Timeliness of ISR	Time from transmission of request to receipt of information (lower is better)
	Increase Successful Data Transmissions	Percent of received and understood data transmissions (higher is better)

(1) Key Performance Parameters

To direct focus on the performance measurements considered the most important to the stakeholders, the team established KPPs. The KPPs, identified in Table 6, each had an objective value (desired goal) and a threshold value (minimum acceptable performance) established by the team members to support initial trade-off analysis of concept designs. Objective and threshold values were related to similar parameters identified for the "standard" Large Vehicle Class UUV and for the VA Class Block III submarine design criteria.

Table 6 – Key Performance Parameters

KPP #	Criteria	Objective	Threshold
1	(LAUNCH SPEED) – To decrease risk of detection, the system shall minimize launch time (time from tube flooded to time UUV is away)	10 Minutes	20 Minutes
2	(RECOVERY SPEED) - To decrease risk of detection, the system shall minimize recovery time (time from UUV manual control is obtained to UUV is stowed)	20 Minutes	40 Minutes
3	(POWER CAPACITY TO UUV) – The system shall replenish the stowed UUV power supply quickly to support re-launch	38 hrs	50 hrs
4	(PAYLOAD VOLUME) - The system shall maximize payload volume to support stowage of multiple UUVs	3000 CUFT	1000 CUFT
5	(COMMUNICATION SUCCESS) – The system shall maximize the percent and received and understood data transmissions.	98% success rate	95% success rate
6	(RELIABILITY) - The system shall maximize the Mean Time Between Failure (MTBF) to minimize maintenance requirements.	24 months	18 months
7	(SAFE OPERATIONAL DEPTH) - The system shall operate at depth to avoid detection and support mission flexibility.	500 feet	150 feet
8	(SYSTEM WEIGHT) - The system shall minimize total weight.	50000 lbs	100,000 lbs
9	(NOISE PREVENTION) - The system shall minimize radiated noise. (i.e. supertanker creates ~ 200 db)	125 db	175 db
10	(SHOCK PREVENTION) - The system shall minimize shock related damage.	Grade A	Grade B

(2) Ranked Needs to KPPs (QFD-1)

To aid with the establishment and prioritization of technical performance measures, QFD models were utilized. The QFD modeling ensured that the customer requirements were reflected accordingly in the final LRS design. When utilized, QFD models established the system requirements and translated them into technical solutions.

The customer requirements identified in QFD-1 were weighted by conducting a pair wise comparison of requirements. The results of the pair wise comparison can be found in Figure 10. In QFD-1, the customer requirements were ranked according to design characteristics identified as the LRS KPPs found in Table 6. By invoking QFD-1, the customer requirements were further understood that allowed the design team to prioritize the customer requirements accordingly. With the prioritized customer requirements, one design approach was compared to another with each customer requirement being satisfied with a technical solution. The results of QFD-1 can be seen in Figure 30 and were incorporated into the QFD-2 model. From the QFD model, it was evident that Launch and Recovery were the two most weighted KPPs identified with an identical percentage rank of 18%.

Customer Requirement (Whats)	*Weights*		Launch Speed *	Recovery Speed *	Power Capacity to UUV *	Launch/Recovery System Stowage Space *	Information Transfer Rate *	Reliability *	Launch/Recovery Depth	Launch/Recovery System Weight	Accoustic Signature *	Shock	
			ft/sec	ft/sec	w	ft^2	mb/sec	%	ft	lbs	db	Grade	
Flexible to accommodate multiple size/shape UUVs	0.073	0.073			3	6							
Support multiple packages/launches simultaneously	0.052	0.052	3	3									
charging	0.123	0.123			9								
Lightweight	0.072	0.072								9			
Affordable	0.091	0.091	3	3									
Resist shock and noise conditions	0.102	0.102									9	9	
Launch/recover performance parameters (time/stealth/moving sub)	0.112	0.112	6	6					6				
Reliable	0.101	0.101						9					
Host ship safety	0.170	0.170	6	6				3	6				
Maintainable at Sea	0.055	0.055	3	3				6					
Interface communications	0.050	0.050					9						
Check Sum		1.00											
Goal Value													
Threshold Value													
Weighted Performance			2.3	2.3	1.3	0.4	0.4	1.7	1.7	0.6	0.9	0.9	12.7
Percent Performance			0.180	0.180	0.105	0.034	0.035	0.137	0.133	0.051	0.072	0.072	

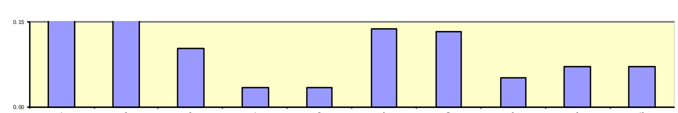


Figure 30 - QFD-1: Customer Requirements vs. KPPs

b. High Level Functional Requirements

Given the performance requirements of the conceptual system, the team sought to describe a functional description to the system. The functional description explains the actions that the system needs to take to reach a specified objective or goal. Using the technical performance parameters established to describe the goals of the system, the team established eight (8) high level functional requirements for the system: execute launch, communicate, system readiness, obtain environmental information, replenish, secure system, power UUV, and maintain system.

(1) Ranked KPPs to Functions (QFD-2)

In a similar fashion to QFD-1, a QFD-2 was created to scale the priority of design characteristics to the high level functional requirements. The constructed QFD-2, shown on Figure 31, effectively ranked the importance of functions in relation to the ranked performance derived in QFD-1 for LRS KPPs. The QFD-2 weighted the performance for each high level function respective to a design characteristic KPP and concluded that Obtaining Environmental Information was the highest ranked function with a weighted percentage of 19.8%. Functionality for Executing Launch and Communicate shared the second ranking with a weighted percentage of 16.1%. The high-level function weighted rankings were then utilized to satisfy QFD-3.

Functions (Hows)

Design Characteristics (KPPs)	Weights		Execute Launch	Communicate	System Readiness	Obtain Environmental Information	Replenish	Secure System	Power UUV	Maintain System	Execute Recovery
			Units	Units	Units	Units	Units	Units	Units	Units	Units
Launch Speed *	0.180	0.180	9			9		6			9
Recovery Speed *	0.180	0.180		9		9		6			
Power Capacity to UUV *	0.105	0.105							9		
Launch/Recovery System Stowage Space	0.034	0.034			9						
Information Transfer Rate *	0.035	0.035	6	6	3		6				6
Reliability *	0.137	0.137			6					9	
Launch/Recovery Depth	0.133	0.133	6	6							6
Launch/Recovery System Weight	0.051	0.051			6						
Accoustic Signature *	0.072	0.072			6			3		3	
Shock	0.072	0.072			6			3		3	
Check Sum		1.00									
Weighted Performance			2.6	2.6	2.4	3.2	0.2	2.6	0.9	1.7	2.6	19.0
Percent Performance			0.139	0.139	0.127	0.171	0.011	0.137	0.050	0.088	0.139

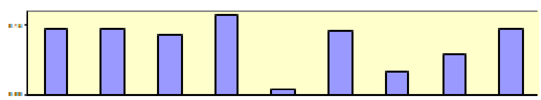


Figure 31 - QFD-2: KPPs vs. Functions

c. Establish Component Concepts from Functions

With system high-level functions established, the team focused on the high level allocation of these functions to system components. The high-level components were the physical sub-systems that will accomplish the desired actions of the system. Although specific allocation of functions between the system components could not be clearly defined without additional examination of the functional architecture, the team established eight (8) core component concepts on which to base a LRS conceptual design: support structure, recovery mechanism, launch mechanism, UUV Power and Recharging mechanism, stowage system, control system architecture, RF Spectrum communications, and acoustic communications.

(1) Ranked Component Concepts to Functions (QFD-3)

Customer requirements, identified in QFD-1, were scaled to system design characteristics, and QFD-2 then analyzed design characteristics which were ranked to high level functions. QFD-3 now used the weighted performances determined in QFD-2 to fit forms to functional requirements. QFD-3 ultimately related LRS form to customer requirements identified in QFD-1 and in Figure 32. QFD-3 concluded that the LRS support structure and control system architecture were the most critical forms necessary to satisfy customer requirements and functionality. Support Structure and Control System Architecture obtained a ranking of 33.8% and 24.9% respectively.

Functions (Whats)	Weights		Support Structure	Recovery Mechanism	Launch Mechanism	UUV Power and Re-Charging Mechanism	Stowage System	Control System Architecture	Radio Frequency Communications	Acoustic Communications	
Execute Launch	0.139	0.139	6		9			6			
Communicate	0.139	0.139							3	3	
System Readiness	0.127	0.127	3			3	6	6			
Obtain Environmental Information	0.171	0.171						6	3	3	
Replenish	0.011	0.011				9	3	3			
Secure System	0.137	0.137	6				9				
Power UUV	0.050	0.050				9					
Maintain System	0.088	0.088						6			
Execute Recovery	0.139	0.139	6	9				6			
Check Sum		1.00									
Weighted Performance			2.9	1.2	1.2	0.9	2.0	4.0	0.9	0.9	14.2
Percent Performance			0.202	0.088	0.088	0.065	0.143	0.283	0.065	0.065	

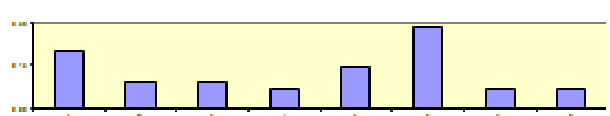


Figure 32 - QFD-3: Functions vs. Form

3. Conceptual Design Alternatives

Conceptual design alternatives are possible physical solutions to the customers' needs. For the LRS, the team sought to identify technologies and concepts for the eight (8) component forms established in the QFD analysis, which could be explored, compared, analyzed and modeled. The conceptual designs established a starting point for all follow-on activities of the project.

Using stakeholder, SME and literature input, the team established potential technologies for each of the component forms. A Technology Matrix was established, as shown in Appendix B, which identified the technology, specific benefits and/or drawbacks to the technology and the potential risk associated with the technology. Risks were assigned a value of high, medium or low in three (3) key categories; Programmatic (Cost/Schedule), Technology Maturity and Perceived Performance.

a. Establish Conceptual Design Alternatives (Morphology)

To determine concepts to analyze further, morphology was used to determine every possible combination of component alternatives. Initially, due to the number of alternatives for each of the eight (8) main components, morphology generated a total of 77,760 conceptual design alternatives. In order to narrow down the number of alternatives, the number of choices for each component was limited. The team considered more component choices (up to 3) for components that had a higher weight in the QFD-3 and limited choices to 1 or 2 for the lower-weighted components. This methodology reduced the morphology list to the top 324 design alternative concepts.

The team established a qualitative measure to compare the remaining alternative concepts. A numerical value was assigned to the remaining components, based on the previously determined levels of programmatic risk, technological maturity, and perceived performance. These values were used to calculate the final score for each combination by taking the sum of the component scores multiplied by the QFD-3 weights for each of the major component. Figure 33 shows the top few lines of the morphology matrix that was used to score the concepts.

	Radio		Acoustic		UUV Power and Re-		Support structure		Recovery		Launch		Stowage		Control		
	Weight =	0.9	Weight =	0.9	Weight =	0.9	Weight =	2.9	Weight =	1.2	Weight =	1.2	Weight =	2	Weight =	4	
Combination	Type	Value	Type	Value	Type	Value	Type	Value	Type	Value	Type	Value	Type	Value	Type	Value	Total
77	Radio frequency	30	Acoustic signals	24	Cable charge with UUV stowed	36	Composite	30	Electro-mechanical Attraction Device	22	Launch Ejection Gas Generator	36	Sealed compartments in payload tube	30	Portable plug-in control system	24	393.6
95	Radio frequency	30	Acoustic signals	24	Cable charge with UUV stowed	36	Composite	30	Remote Vehicles (ROV)	22	Launch Ejection Gas Generator	36	Sealed compartments in payload tube	30	Portable plug-in control system	24	393.6
59	Radio frequency	30	Acoustic signals	24	Cable charge with UUV stowed	36	Composite	30	Articulated Mechanical Arm	14	Launch Ejection Gas Generator	36	Sealed compartments in payload tube	30	Portable plug-in control system	24	384
239	Radio frequency	30	Acoustic signals	24	Hostsub releases charging cable	24	Composite	30	Electro-mechanical Attraction Device	22	Launch Ejection Gas Generator	36	Sealed compartments in payload tube	30	Portable plug-in control system	24	382.8
257	Radio frequency	30	Acoustic signals	24	Hostsub releases charging cable	24	Composite	30	Remote Vehicles (ROV)	22	Launch Ejection Gas Generator	36	Sealed compartments in payload tube	30	Portable plug-in control system	24	382.8
83	Radio frequency	30	Acoustic signals	24	Cable charge with UUV stowed	36	Composite	30	Electro-mechanical Attraction Device	22	Release a catch (UUV "swims" away on its own)	24	Sealed compartments in payload tube	30	Portable plug-in control system	24	379.2
101	Radio frequency	30	Acoustic signals	24	Cable charge with UUV stowed	36	Composite	30	Remote Vehicles (ROV)	22	Release a catch (UUV "swims" away on its own)	24	Sealed compartments in payload tube	30	Portable plug-in control system	24	379.2

Figure 33 - Morphology Matrix

b. Assumptions for Conceptual Design Alternatives

Several assumptions were made by the Capstone team members in order to rank the eight (8) main component combinations.

- Risk rankings for each component alternative were correct, based on team experience, literature research and discussion with peers.
- Identified risk ratings were used to narrow down the number of alternatives for each component, based on the assumption that the lower rated alternatives would not make it into the top ranked concepts.

- In scoring the alternatives based on their risk ranking, the team developed a 1/3/9 point ranking system for risk scores of red, yellow and green respectively. The 1/3/9 point system has precedence, being based on QFD ranking models [Clausing, 1994, pg. 124], and was found to provide the most robust differentiation between alternatives.
- The team weighed the performance risk twice as much as the programmatic risk and technical maturity to align with stakeholder values and needs to field an advanced concept.

Figure 34 shows how the score was calculated for each individual component alternative.

		Weight =	1	Weight =	1	Weight =	2	
Major Component	Technology	Cost/Schedule		Tech Maturity		Performance		Total score
Support Structure	Carbon Steel	Low	9	Mature	9	Low	1	20
	Composite	Medium	3	Mature	9	High	9	30
	Titanium	Low	9	Mature	9	Medium	3	24
Recovery Mechanism	Articulated Mechanical Arm	Medium	3	Mature	9	Low	1	14
	Remote Vehicles (ROV)	High	1	Prototype	3	High	9	22
	Electro-mechanical Attraction Device	High	1	Prototype	3	High	9	22
Launch Mechanism	Launch Ejection Gas Generator	Low	9	Mature	9	High	9	36
	Release a catch (UUV "swims" away on its own)	Low	9	Mature	9	Medium	3	24
	Articulated Mechanical Arm	Medium	3	Mature	9	Low	1	14
UUV Power and Re-Charging Mechanism	Physical cable connection (while UUV stowed)	Low	9	Mature	9	High	9	36
	Hostsub releases charging cable (while UUV launched)	Low	9	Mature	9	Medium	3	24
Stowage System	Catch/lock/clasp in payload tube	Medium	3	Mature	9	Medium	3	18
	Magnet in payload tube	High	1	Prototype	3	High	9	22
	Sealed compartments in payload tube	Medium	3	Mature	9	High	9	30
Control System Architecture	Portable plug-in control system	Low	9	Mature	9	Medium	3	24
	Hardwired integrated system	Medium	3	Mature	9	Low	1	14
Radio Communication	Radio frequency	Low	9	Prototype	3	High	9	30
Acoustic Communication	Acoustic	Medium	3	Prototype	3	High	9	24

Figure 34 - Component Alternative Scores

4. Results, Feasibility and Risks

The results of the conceptual design alternative analysis, scoring, ranking and team decision-making identified top design alternatives suited for additional analysis and comparison.

All alternatives share several key components, such as underwater, short-range radio communication capabilities and an acoustic homing communication feature. These communication technologies were deemed the most suitable and cost-effective components available to serve the short-range communications needs of the system and no other technologies were considered. Additionally, all alternatives will utilize a portable plug-in type hardware/software control system, similar to systems now utilized for many temporary alternations supported on submarines. Such systems are easy to maintain and up-grade when compared to hardwired systems as work can be done in a laboratory environment vice an industrial facility. However, all the alternatives did have significant differences, most notably with UUV recovery devices, materials for the physical structure and UUV battery charging capabilities. These core component areas address many of the challenges and issues brought up during stakeholder needs analysis and provide the best comparisons between conceptual system alternatives and baseline systems that currently exist. The alternatives, identified in Table 7 with respect to their component composition, are discussed in greater detail below:

Table 7 – Composition of Concept Alternatives

	Baseline - Low Cost Option	**Alternative 1 – Attraction Recovery**	**Alternative 2 – Mechanical Recovery Arm**	**Alternative 3 – ROV Recovery**	**Alternative 4 – Performance Option**
Support Structure	Carbon Steel	Titanium	Carbon Fiber Composite	Titanium	Carbon Fiber Composite
Recovery Mechanism	"Swim to Cradle"	Electro-Mechanical Device	Articulated Mechanical Arm	Tethered ROV	Electro-Mechanical Device
Launch Mechanism	"Swim Away"	Pressurized Gas Ejection	Pressurized Gas Ejection	Pressurized Gas Ejection	Electro-Mechanical Device
UUV Re-charging Mechanism	Wet Cable Connection, UUV Stowed	Dry Cable Connection, UUV Stowed	Dry Cable Connection, UUV Stowed	Dry Cable Connection, UUV Stowed	Inductive Charging (Touch Pad) UUV Stowed
UUV Stowage System	Mechanical Locks	Sealed/Dry Compartment in Tube	Sealed/Dry Compartment in Tube	Sealed/Dry Compartment in Tube	Magnetic Lock
L&R Control System Architecture	Portable, Plug-in Control Hardware/ Software	Portable, Plug-in Control Hardware/ Software	Portable, Plug-in Control Hardware/ Software	Portable, Plug-in Control Hardware/ Software	Portable, Plug-in Control Hardware/ Software
Short-Range RF Communications	Underwater Radio Waves	Underwater Radio Waves	Underwater Radio Waves	Underwater Radio Waves	Underwater Radio Waves
Acoustic Homing Communications	Acoustic Homing Beacon	Acoustic Homing Beacon	Acoustic Homing Beacon	Acoustic Homing Beacon	Acoustic Homing Beacon

Baseline – Low Cost Option

The Baseline Option, considered the lowest cost option available, attempted to mirror the technology and design of the ULRM system built and tested on a converted missile tube of the USS FLORIDA (SSGN 728) during Operation "Giant Shadow". [Galrahn, 2006] This option did not utilize any technology to support UUV recovery. Instead, the baseline option relied on the UUV's ability to accurately "home-in" on the submarine location and deployed cradle above the VPT. The UUV would be required to navigate to the clamping device which will capture the horizontal UUV, re-orient it to the vertical position and stow it within the VPT. It was expected that the host submarine would be nearly stationary to support UUV recovery. Likewise, the

UUV "swim away" method of launch would require the submarine to come to a virtual stop to prevent a collision between the host sub and the slow moving UUV.

The Baseline Option structural composition was made of variety of materials with the major portion being high yield strength carbon steel (HY-80). While this material is easy to machine or weld, it is susceptible to corrosion in a normally wetted environment and must be painted to prevent oxidation. Additionally, as HY-80 weighs more than 2x that of Titanium and 6x that of carbon fiber reinforced polymers of equal volume, the HY-80 structure adds significant weight to the forward end of the VA Class Block III submarine, which must be compensated by additional ballast aft.

The Baseline Option stowed the UUV in its cradle when retracted into the tube. The cradle secures the UUV with a series of mechanical locks and clasps in its vertical position along a series of guide rails. As a UUV might remain in-service for up to 18 months, within a wet stowage condition, normal and usual mechanical wear and corrosion of mechanical parts would likely create conditions of gear backlash or lost motion. The result could be a less secure stowage of the 20,000 lb UUV and vibration which results in some radiated noise.

When developed for the SSGN missile tube, the ULRM design leveraged off of the existing missile tube flood and drain system to de-water the tube and support dry data transfer and battery re-charging. As a flood and drain system was not a design feature of the VPT for the VA Class Block III submarine, the Baseline Option relied on cable re-charging of the battery in a wet environment. This wet environment greatly increased the risk of a flooded cable, which would jeopardize underway UUV replenishment. The Block IV variant of the VA Class submarine design may provide a means to dewater and access the VPT; however, this capability will not be explored in this project. Figure 35 provides a conceptual representation of the Baseline Low Cost Option.

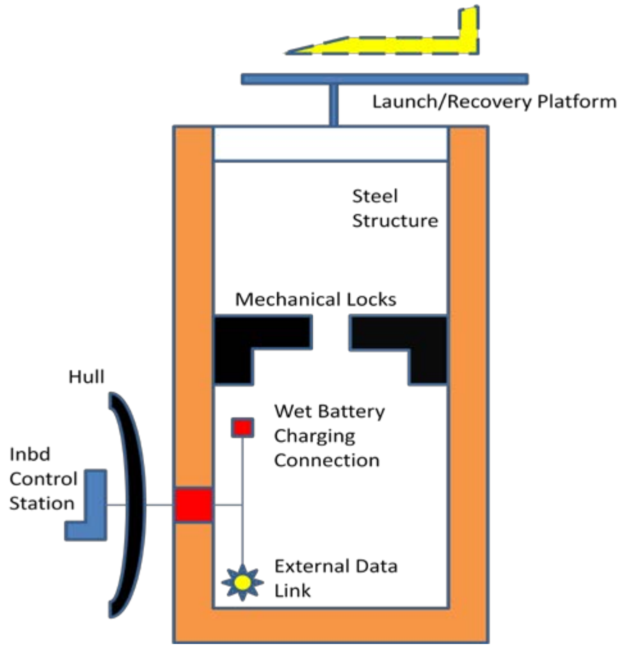


Figure 35 – Baseline (Low-Cost Option) Concept Alternative

Alternative 1– Attraction Recovery

The Attraction Recovery alternative used technologically advanced components in the LRS structure and the recovery mechanism itself to address the concerns of stakeholders with regards to currently fielded systems. The key to this alternative was an Electro-Magnetic Propulsion (EMP) device, which accelerated an object using a flowing electrical current and magnetic fields. In seawater, such a device would charge the fluid which then can be repelled. The low pressure area near the EMP device, caused by the vacating seawater, would create a current which could draw the UUV into a recovery cradle. If successful, such a device would allow rapid recovery of a UUV while both the submarine and UUV maintain a positive forward momentum, would be multi-directional and would not impose significant structural stresses on the support structure.

To counter the stresses put on the structure by mechanical launch and recovery devices, the proposed structural material for this option was titanium. This material provides superior strength and elongation properties over the comparative materials, should not have a significant galvanic impact with adjacent materials found in the forward end of the VA Class Block III submarine and should resist the forces imposed during launch and recovery. However, titanium weighs about 3 times as much by volume as a carbon fiber composite material, thereby affecting submarine stability at relatively the same cost per pound.

Other features found in this alternative were a pressurized gas launch system, found in existing missile launch systems, meant to rapidly deploy the UUV away from the host submarine and limit collision mishaps. This alternative featured a dry stowage compartment within the VPT where UUV battery charging and information transfer can occur without significant risk of electrical shorts or data disruptions. In the VA Class Block III submarine concept, the dry compartment would not be accessible to technicians to support physical contact with the UUV while underway. However, the dry compartment would still provide a benefit of protecting the UUV modules from constant seawater exposure and corrosion/degradation during a mission cycle, thereby improving system reliability. Figure 36 provides a conceptual representation of Alternative 1.

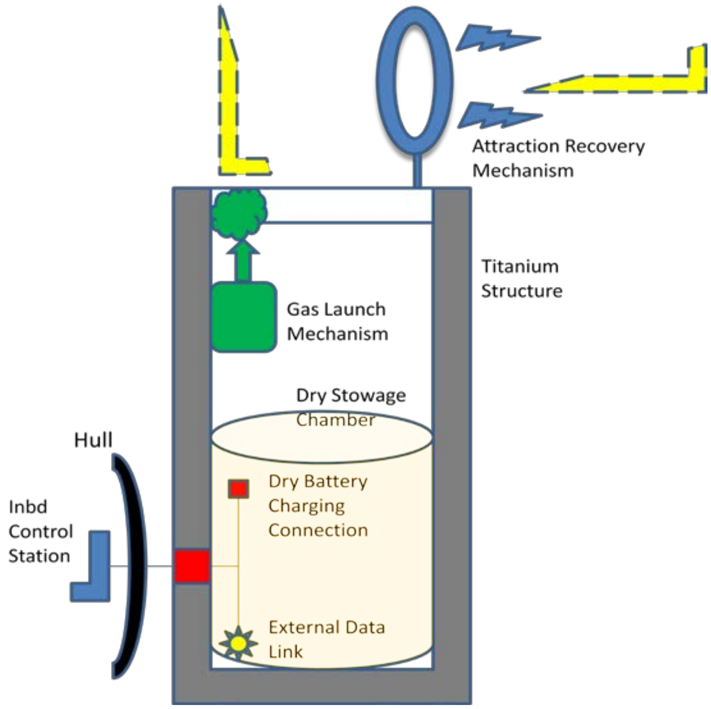


Figure 36 – Alternative 1 (Attraction Recovery) Concept Alternative

Alternative 2 – Mechanical Recovery Arm

The Mechanical Recovery Arm Alternative utilized an articulated mechanical arm to support recovery of the UUV. This type of robotic arm would have approximately a 270° degree of motion, with the VPT hatch preventing full field recovery. The arm would be directly controlled from inside the submarine with attached cameras and sensors providing feedback to the operator. Unlike the Attraction Recovery Alternative, interaction between the mechanisms would require the UUV to successfully navigate much closer to the host submarine, posing a greater risk for collision. Additionally, the UUV and submarine would likely come to a near stop to support recovery. However, the articulated arm design is currently used in many undersea applications and the technology has proven mature and successful.

This alternative sought to use a carbon fiber reinforced polymer to add stiffness and tensile strength to the support structure, at a weight six times less than carbon steel structures of the same volume. The stiffness of the carbon fiber structure should limit vibrations and consequential radiated noise. It could be designed to limit compressive loading and allow modular upgrades by adding or removing sections via mechanical fasteners. Drawbacks of this material would include a low resistance to compression and shear stresses which may be countered through careful design.

The dry stowage feature, dry power charging component and gas launch technology for the Mechanical Recovery Arm Option was identical to that for the Attraction Recovery Option. Figure 37 provides a conceptual representation of Alternative 2.

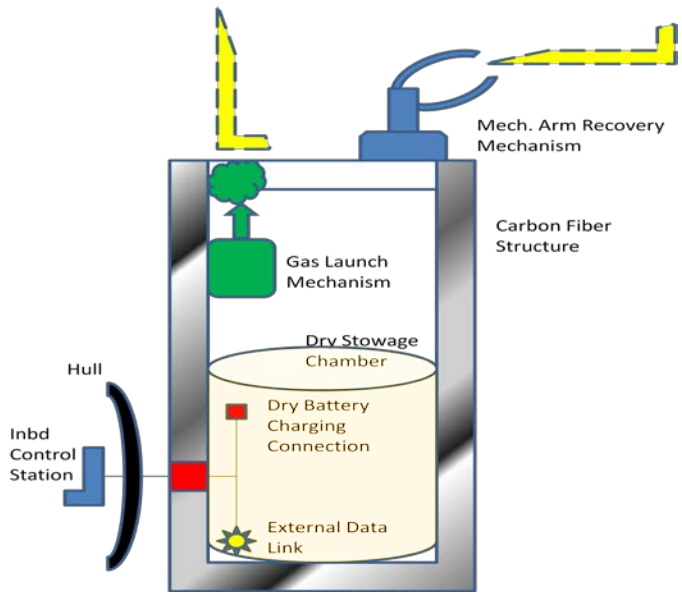


Figure 37 – Alternative 2 (Mechanical Recovery Arm) Concept Alternative

Alternative 3 – Remotely Operated Vehicle (ROV) Recovery

The ROV Recovery Alternative utilized small, tethered, ROVs to support recovery of the UUV. These vehicle(s) would swim out to meet the UUV, attach to the UUV and tow it, via the tethered feature, back into the VPT. The ROVs would be controlled from inside the submarine with attached cameras or sensors providing feedback to the operator.   This recovery option would allow capture of the UUV at a distance, limiting the potential for collision mishaps between the UUV and submarine. Additionally, the submarine and UUV would be able to maintain a forward momentum during the recovery operation. Although underwater ROVs are used in many operations and are a mature technology, such equipment would itself be subjected to possible impact damage, demanding a redundancy feature at an extra cost. Furthermore, ROVs are complex and will require significant underway maintenance to ensure the systems reliability for the proposed operating cycle.

The components for dry stowage, titanium structure, battery re-charging and gas launch for the ROVs Recovery Option was identical to the components for the Attraction Recovery Option. Figure 38 provides a conceptual representation of Alternative 3.

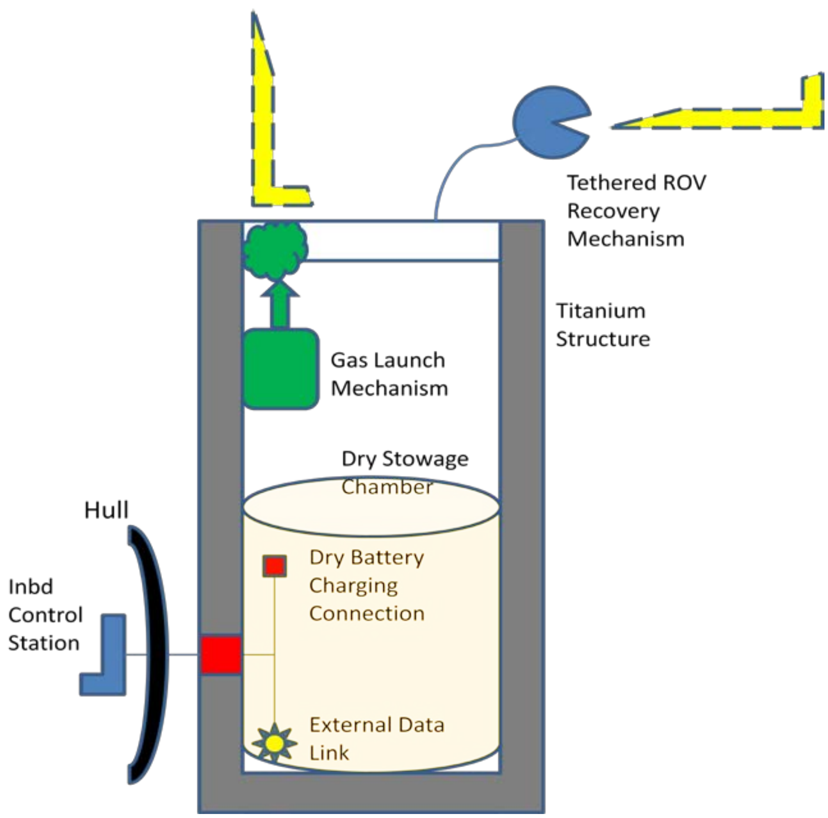


Figure 38 – Alternative 3 (ROV Recovery) Concept Alternative

Alternative 4 – Performance Option

The Performance Option utilized cutting-edge technology to provide the most superior system for the stakeholder. However, with performance, programmatic issues such as cost and schedule may be adversely impacted due to technology development issues.

Like the Attraction Recovery Option, the Performance Option will use an EMP device to recover the UUV at a distance. Additionally, this option utilized the same EMP device to launch the UUV simply by reversing the magnetic field. If successful, this feature would support both launch and recovery of UUV at speed while eliminating the need for an additional launching mechanism.

The Performance option utilized a carbon fiber composite structure to support the equipment necessary for an electro-magnetic suspension stowage system within the tube. The electro-magnetic suspension stowage system restrained the stowed UUV within the tube without physical contact. Without physical contact, the UUV would be less prone to vibration damage and to generation of radiated noise. This option would require power and computer-regulated feedback of the magnetic field and would require significant technological considerations over mechanical stowage systems.

The battery re-charging component package on the Performance Option used inductive charging. Inductive charging uses an electro-magnetic field to transfer energy between objects, in this case, the UUV and a charging pad. Induction chargers use an induction coil to create an alternating electro-magnetic field at the base station (charging pad) and a second induction coil in the portable component (UUV) takes power from the electro-magnetic field and converts it back into electrical current to charge the battery. Charging could successfully occur in a wet environment even when there is a small gap between the components and has a lower risk of electrical shock or short circuit as there are no exposed conductors. Disadvantages to this technology included lower efficiency of power transfer when compared to conductive charging and heat build-up in components. Figure 39 provides a conceptual representation of Alternative 4.

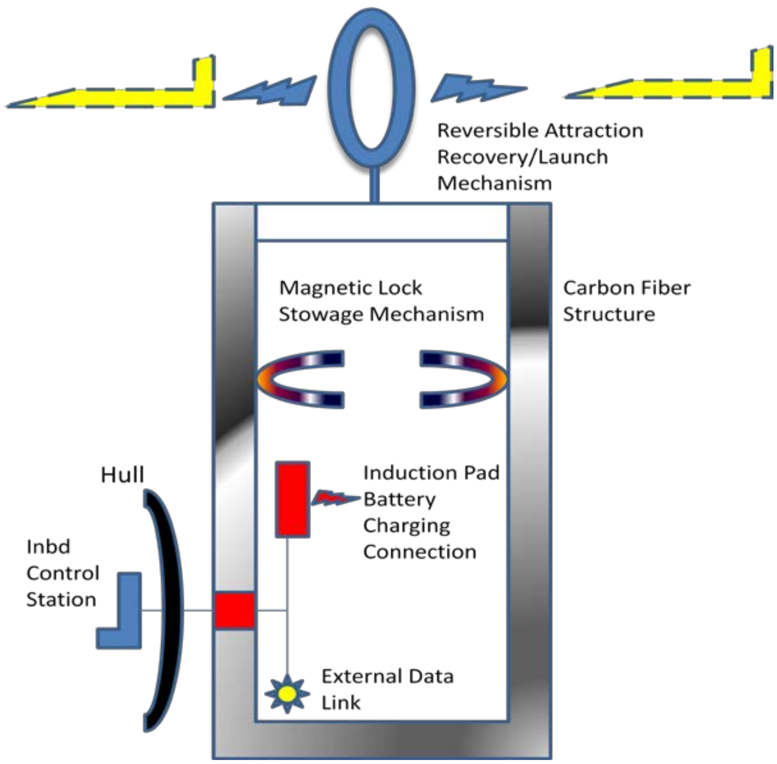


Figure 39 – Alternative 4 (Performance Option) Concept Alternative

a. Feasibility Screening

Feasibility screening was accomplished as an initial step towards risk analysis for each conceptual design alternative. Each conceptual alternative was evaluated against the KPPs, identified in Table 6, to determine if the concept could reasonably meet the assigned threshold values. For each KPP, a color-coded value was assigned (Green – Likely to Meet Objective; Yellow – Marginal Risk in Meeting Threshold; Red – High Risk in Meeting Threshold). The results of this screening are contained in Table 8.

Table 8 – Feasibility Analysis of Concept Alternatives

ALT / KPP	Baseline	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Launch Speed	H	L	L	L	L
Recovery Speed	H	L	M	L	L
Power Capacity to UUV	H	M	M	M	M
Payload Volume	L	M	M	M	L
Communications (Transfer Rate)	M	L	L	L	M
Reliability	L	M	M	M	M
System L & R Depth	M	L	M	L	L
System Weight	H	L	M	L	L
Noise Prevention	M	M	M	M	L
Shock Prevention	M	M	M	M	L

Legend –

H	- High Risk of Not Achieving KPP Threshold
M	- Moderate Risk of Not Achieving KPP Threshold
L	- Low Risk of Not Achieving KPP Threshold

Feasibility screening in this context did not eliminate any alternatives from consideration. During the analysis of potential technologies conducted in support of the morphology matrix, the team discounted any component alternatives that placed personnel (divers) in harm's way as well as component alternatives with very little likelihood of success.

b. Risk Analysis and Mitigation Approaches

Risk is a measure of future uncertainties in achieving program performance goals and objectives within defined cost, schedule, and performance constraints. The Risk Management Process Model, as described in the Risk Management Guide for DoD Acquisition [DAU, 2006], consists of five activities: risk identification, risk analysis, risk mitigation planning, risk mitigation plan implementation, and risk tracking. The Project Management Plan, Appendix A, further described the steps taken by the Capstone team to identify, analyze and propose risk mitigation solutions for the concept alternatives. Mitigation plan implementation proposals and risk tracking was recommended at final concept selection for potential carry-through into post-Milestone "A" system development.

Risk identification and analysis captured system technical, cost, schedule and programmatic for each of the concept alternatives. Technical risks included considerations for performance, interfaces, quality of design and components. Costs risks included acquisition considerations such as Technology Readiness Level (TRL) and development costs as well as long term costs such as maintenance, manpower and logistics concerns. Schedule risks included material supply issues and resource issues, both in acquisition and long-term maintenance. Programmatic risks involved a wide range of internal and external concerns, such as mission and requirements creep, contractor issues and sponsor/stakeholder considerations such as funding shortfalls. Risks were identified and analyzed using the judgment and experience of team members, literature research, lessons learned from past system acquisition and operations and forecasting of future events.

Risk consists of three components: (1) future risk root cause; (2) likelihood of occurrence; and (3) consequence of the occurrence. At the concept alternative phase of this project, a qualitative approach to risk analysis was determined to be better, suited as a quantitative approach requires specific knowledge with respect to technologies and components. For each identified risk, a likelihood of occurrence was assigned and rated on a scale of “A” to “E”. A rating of “A” indicated the risk was “Not Likely” (probability of ~10% occurrence) while a rating of “E” indicated the risk was a “Near Certainty” (probability of ~ 90% occurrence). Ratings of “B”, “C” and “D” conform to a probability of 30%, 50% and 70%, respectively. Likewise, the consequence that results from the occurrence of the risk was rated on a scale of “1” to “5” where a rating of “1” indicated minimal impact to performance, cost and/or schedule which results in no change to program decisions while a rating of “5” indicates severe performance, cost and/or schedule impact which will likely jeopardize the program. Ratings of “2”, “3” and “4” designated impacts were considered minor, moderate and significant, respectively, to program parameters.

Technical, schedule, performance and programmatic risks for each concept alternative were identified by root cause and assessed a likelihood and consequential severity. If considered feasible, a mitigation solution was recommended for each risk. Table 9 provides a listing of risks and the assessment of the risks for each concept alternative.

Table 9 – Risk Identification and Analysis Matrix

Concept	Risk Identification	Root Cause / *Rating*	Mitigation Proposal
Baseline	Performance Risk 1	Risk that UUV "Swim In" recovery speed cannot meet KPP / *Assessed as D5*	Re-negotiate KPP requirements with stakeholders
	Performance Risk 2	Risk that UUV Battery replenishment components cannot meet KPP for replenishment time / *Assessed as C5*	Re-negotiate KPP requirements with stakeholders
	Performance Risk 3	Risk that system weight will not meet KPP requirements / *Assessed as C5*	Re-negotiate KPP requirements with stakeholders
	Cost Risk	Risk that choice of materials (HY-80) and sliding components will result in more maintenance costs / *Assessed at C3*	Create robust underway preventative maintenance program
	Schedule Risk	No schedule risks are anticipated	
	Programmatic Risks 1	Risks that requirements/mission changes cannot be accommodated due to low tech levels / *Assessed at C3*	Implement flexibility requirements in detailed design
	Programmatic Risks 2	Risks that UUV contractors will design a future concept that cannot be accommodated by cradle design / *Assessed at B3*	Limit acceptable design requirements for contractors in baseline design considerations
Alt 1 – Attraction Recovery	Performance Risk 1	Risk that recovery system will not generate enough seawater current to recover UUV / *Assessed as B5*	Increase shipboard power capabilities
	Performance Risk 2	Risk that dry seal stowage compartment will not work, impacting battery charging and data transfer / *Assessed as A4*	Add redundancy to stowage compartment design
	Cost Risk 1	Risk that Attraction recovery system will overrun development costs / *Assessed as D3*	Budget for technology development
	Cost Risk 2	Risk that titanium structure requires significant skills and materials for manufacture / *Assessed as D3*	Conduct early robust training/stockpile materials

Table 9 – Risk Identification and Analysis Matrix (Continued)

Concept	Risk Identification	Root Cause / *Rating*	Mitigation Proposal
Alt 1 – Attraction Recovery (Cont.)	Cost Risk 3	Risk that specialized skills and materials are required to maintain Attraction Recovery mechanism / *Assessed as C3*	Stockpile logistic equipment and conduct robust training program early in program
	Schedule Risk	Risk that technology development of Attraction Recovery system could delay fielding system / *Assessed at B2*	Program float into schedule to mitigate delay impacts
	Programmatic Risk 1	Risk that budget constraints could reduce funding for program / *Assessed at C3*	Assign financial roles to experienced personnel to mitigate shortfalls / allocate resources
	Programmatic Risks 2	Risks that UUV contractors will design future concept not accommodated by Attraction Recovery mechanism / *Assessed at B3*	Limit acceptable design requirements for contractors in baseline design considerations
Alt 2 – Mechanical Recovery	Performance Risk 1	Risk that mechanical arm will not recover the UUV with system requirements / *Assessed as C4*	Design system with length, rapid recovery features
	Performance Risk 2	Risk that dry seal stowage compartment will not work, impacting battery charging and data transfer / *Assessed as A4*	Add redundancy to stowage compartment design
	Performance Risk 3	Risk that composite structure fails early under launch and recovery operations / *Assessed as B3*	Design to resist shear/ employ shock absorbing devices
	Cost Risk	Risk that underwater recovery arm mechanism will overrun development costs / *Assessed as B3*	Budget for technology development
	Schedule Risk	Risk that technology development of mechanical arm could delay fielding system / *Assessed at B2*	Program float into schedule to mitigate delay impacts
	Programmatic Risks 1	Risks that requirements/mission changes cannot be accommodated due to limits of mechanical arm / *Assessed at B3*	Implement flexibility requirements in detailed design
	Programmatic Risks 2	Risks that UUV contractors will design a future concept that cannot be accommodated by mechanical arm recovery mechanism / *Assessed at B3*	Limit acceptable design requirements for contractors in baseline design considerations

Table 9 – Risk Identification and Analysis Matrix (Continued)

Concept	Risk Identification	Root Cause / *Rating*	Mitigation Proposal
Alt 3 – ROV Recovery	Performance Risk 1	Risk that ROVs recovery will not support timely recovery of UUV / *Assessed as B3*	Increase size and power of ROVs
	Performance Risk 2	Risk that dry seal stowage compartment will not work, impacting battery charging and data transfer / *Assessed as A4*	Add redundancy to stowage compartment design
	Cost Risk 1	Risk that ROV recovery system will overrun development costs / *Assessed as C3*	Budget for technology development
	Cost Risk 2	Risk that titanium structure requires significant skills and materials for manufacture / *Assessed as D3*	Conduct early robust training/stockpile materials
	Cost Risk 3	Risk that specialized skills and materials are required to maintain ROV mechanisms / *Assessed as D3*	Stockpile logistic equipment and conduct robust training program early in program
	Schedule Risk	Risk that technology development of ROV Recovery system could delay fielding system / *Assessed at B2*	Program float into schedule to mitigate delay impacts
	Programmatic Risk	Risk that budget constraints could reduce funding for program / *Assessed at C3*	Assign financial roles to experienced personnel to mitigate shortfalls and concentrate on resource allocation to minimize impacts
Alt 4 – Perform Option	Performance Risk 1	Risk that launch/recovery system will not generate enough seawater current to recover UUV / *Assessed as B5*	Increase shipboard power capabilities
	Performance Risk 2	Risk that battery charging system will not have enough efficiency to charge UUV timely w/o excessive heat generation / *Assessed as B2*	Design system to minimize heat loading
	Performance Risk 3	Risk that composite structure fails early under launch and recovery operations / *Assessed as B3*	Design to resist shear/ employ shock absorbing devices

Table 9 – Risk Identification and Analysis Matrix (Continued)

Concept	Risk Identification	Root Cause / *Rating*	Mitigation Proposal
Alt 4 – Perform Option (Cont.)	Cost Risk 1	Risk that multiple systems will overrun development costs / *Assessed as D3*	Budget for technology development
	Cost Risk 2	Risk that specialized skills and materials are required to maintain Attraction Device and battery charging mechanisms / *Assessed as D3*	Stockpile logistic equipment and conduct robust training program early in program
	Schedule Risk	Risk that technology development of multiple systems could delay fielding system / *Assessed at C2*	Program float into schedule to mitigate delay impacts
	Programmatic Risk	Risk that budget constraints could reduce funding for program / *Assessed at C3*	Assign financial roles to experienced personnel to mitigate shortfalls and concentrate on resource allocation to minimize impacts

Risks were graphically represented and compared on a risk matrix. The risk matrix was made up of three colors that denote increasing levels of risk. The green, yellow and red blocks of the risk matrix indicate low, medium and high risks, respectively. To support the comparison of all five (5) alternatives on one risk matrix, the technical, schedule, performance and programmatic risks were weighted to develop one average risk rating for the concept. Using the stakeholder requirements and value system, performance and costs were the two most important considerations in fielding a successful system. Furthermore, while life-cycle costs were considered important for all systems, performance issues, particularity UUV recovery and power considerations hamper the effectiveness of existing systems. The following equation was used to develop one average risk rating for each concept alternative:

$$OverallAvergeRisk = (4\sum PR + 2\sum CR + \sum SR + \sum \Pr ogR) / \#ofRisks$$

Where: PR is Performance Risk;
CR is Cost Risk;
SR is Schedule Risk;
And ProgR is Programmatic Risk

Table 10 provides the results of overall risks for each concept alternative while Figure 40 shows the comparative risk matrix for the five (5) concept alternatives.

Table 10 – Overall Risk Value for Each Alternative

Concept	∑(PR)	∑(CR)	∑(SR)	∑(ProgR)	Final Average Risk Value
Baseline	C5	C3	NA	C3	C5
Alt 1	B4	D3	B2	C3	C3
Alt 2	B4	B3	B2	B3	B3
Alt 3	B3	D3	B2	C3	C3
Alt 4	B3	D3	C2	C3	C3

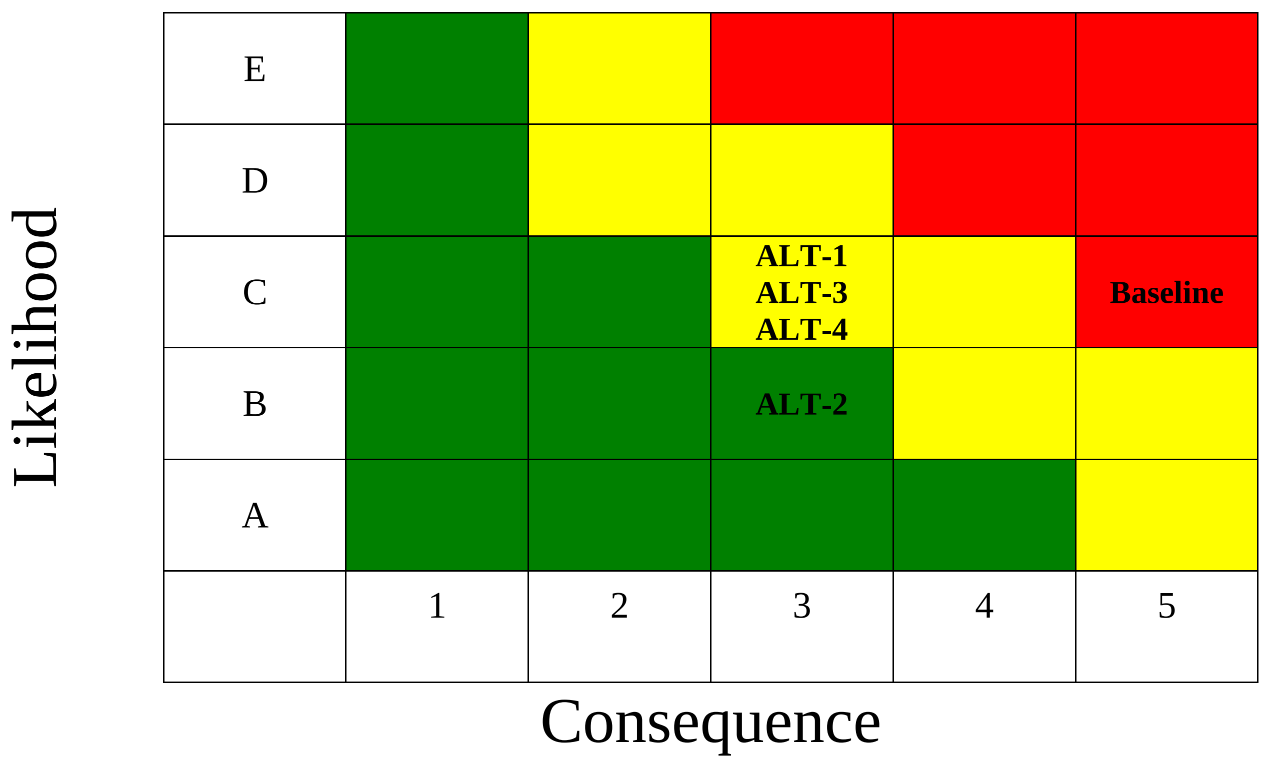


Figure 40 – Concept Alternative Risk Matrix

c. Risk Analysis Conclusion

Risk analysis with the assigned weighting factors found the best concept alternative to be Alternative 2, Mechanical Recovery Arm. This system had a likely chance of UUV recovery within the performance parameters while offering a system with lower developmental and long-term cost risks. System structural design using carbon fiber composite materials over titanium and steel provided a significant weight advantage at a compatible structural strength assumed needed for this system. Cost risks for carbon fiber structures were considered negligible as it was assumed that materials will be purchased and received in a completed form (no molds or special skills would be required for assembly).

To verify that weighting method that favored performance risks over the other risks did not significantly bias the decision, the team ran another set of calculations, this time with all risk factors equal. These results found no change in the risk rankings of the four (4) alternative options; however, with the Baseline Option no longer penalized for poor performance, it was now ranked Yellow vice Red. Since the ranking order of the options remained constant through two different weighting options, the team deemed the assumptions made that arrived to the results of Table 10 a valid approach.

Although Alternative 2 was deemed to be the least risky, it was not significant better than Alternatives 1, 3 or 4 to completely discount any of these alternatives. However, the Baseline Option was significantly worse than all other options due to performance concerns. If verified as a weak performer via Modeling and Simulation, the Baseline option would not be considered the best choice with the given set of performance KPPs.

B. COST ANALYSIS

1. Background

Referring to the F-35 Joint Strike Fighter Program, Defense Secretary Robert Gates remarked that "…the nation can no longer afford the quixotic pursuit of high-tech perfection that incurs unacceptable cost and risk…"[Scully, 2010] In response to this and many other examples of uncontrolled cost growth in defense spending, the Under Secretary of Defense issued a memorandum mandating affordability as a requirement for defense acquisition programs. [Carter, 2010] In this context, affordability was no longer viewed as the cost to design, build, test and field a weapons system, but instead is viewed as the life-cycle cost (LCC) of the system which included: training, interface and integration with other systems and platforms, to absorb the system into a mission area, operational and support costs, and disposal costs. To understand and compare the total life-cycle costs of the five (5) conceptual alternatives in same year dollars, the team performed a life-cycle cost analysis to determine economic equivalence. Material choices and decisions made during design and construction of the systems were more often than not the result in a false sense of affordability. Low end products and technologies, while affordable in terms of acquisition dollars resulted in exponential sustainment costs due to premature failures and the need for constant upgrades. Likewise, cutting edge equipment might not provide its worth if it significantly taxes development budgets and requires modifications to many external boundary systems to work. The results of the life-cycle cost analysis were used as a tool during trade-off analysis and final selection of the recommended concept.

2. Methodology

Life cycle cost estimates were established for each of the alternatives identified in Table 7 in three (3) areas; Acquisition, Operations and Sustainment & Indirect Costs. Primarily, cost estimates were developed using cost data from like vendor sources and from team member experiences in submarine repair, operations and sustainment. Beyond obvious acquisition costs differences that result from using different materials and technologies, assumptions were established to differentiate expected repair cycles and costs for each alternative. To establish a value in current year dollars and eliminate the effects of inflation, a real discount rate of 1.7% was used for a system service life of 20 yrs. [OMB, Circ. A-94, 2010] As no concept alternative was expected to contain a significant amount of hazardous materials, disposal costs were deemed to be constant for all alternatives and, therefore, were not considered in a comparison analysis. Also, since the system concept has established static external boundaries for the Standard Large Vehicle Class UUV and the VPT, all concept alternatives were considered equal with respect to modifications on external systems. Finally, a sensitivity analysis was conducted on high cost drivers (those items that contributed more than 10% to the overall life-cycle costs) to determine how changes in assumptions affected the output costs. Variations were made to the input assumptions and changes were modeled to help establish a valid cost range for each concept alternative.

a. Cost Analysis Assumptions

To provide a basis for cost analysis, the project team assumed:

- The UUV LRS would be fielded and maintained is a similar fashion to other major submarine support equipment such as a SEAL Delivery Vehicle.

- The anticipation is 7 VA Class Block III submarines and 9 VA Class Block IV submarines with a VPT would be fielded, with an equal number assigned to the Atlantic and Pacific fleets.
- As persistent-ISR would be only one of many core submarine missions, no more than four (4) UUV LRSs would be in use at any one time. This is consistent with the employment concept of VA Class submarines for SOF-type missions.
- At least two (2) complete systems each would ultimately be fielded on in the Atlantic and Pacific areas of operation beginning in FY+10, when VA Class Block IV submarines are scheduled to be commissioned.
- An initial increment (INCR-1) would be fielded upon program inception with an improved and upgraded increment (INCR-2) planned for release to coincide with Block IV submarines.
- For concept alternatives where reliability may be at issue (in particular, composite and steel structures), at least one (1) spare system would be available which can be transported as necessary to support maintenance and repair needs. For systems anticipated to require more maintenance cycles, additional spares would be required.
- Based on the UUV roadmap report of 2004, the useful life of the LRS will be considered at 20 years. Significant technology advances and mission profiles were likely in the future that would render the VPT launched and recovered UUV obsolete after 20 years of service.
- In the 20 year life, each system would be in-service for 50% of the time and awaiting deployment or in maintenance for 50% of the time. During the service life, each system would undergo one (1) major overhaul/modernization period at the half-life

and minor/moderate sized overhauls every two to four years, depending on the assessed reliability of the system.

- The cost for the materials and labor for each overhaul were considered to approximate submarine maintenance costs, as similar facilities are expected to maintain the systems.
- For the moderate/major availability, estimates were considered to be 15% of acquisition costs. For minor availabilities, estimates were 1-3% of acquisition costs. These percentages aligned with typical submarine maintenance costs.
- Because production costs vary greatly between manufacturers and were difficult to reliably estimate, open market price per pound of the different materials used in the support structure were used in the cost analysis.
- To validate the assumptions of concept acquisition costs, a comparison was made to a similar, fielded system, the Multiple All-Up Round Canister (MAC). Using assumptions for MAC material and labor costs, the team developed an estimate close to the known costs of a MAC.
- By applying the same structure and labor assumptions to the five (5) concept alternatives, the obtained acquisition costs were considered reasonable and appropriate.

3. Life Cycle Cost (LLC) Analysis

a. Concept Acquisition Costs

Acquisition cost considerations for conceptual alternatives were established by using cost data from internet and peer sources for exact or similar equipment. Appendix C provides more detailed sources and estimates as to how the team arrived at the cost estimates for each alternative. Table 11 provides the summarized Acquisition Cost analysis for each concept alternative on a per unit basis.

Table 11 – Acquisition Costs for One Unit of Each Alternative Concept

	Baseline - Low Cost Option		Alternative 1 – Attraction Recovery		Alternative 2 – Mechanical Recovery	
	Technology Option	Cost	Technology Option	Cost	Technology Option	Cost
Support Structure	Carbon Steel	$ 1,612,750	Titanium	$ 12,577,750	Composite	$ 5,892,000
Recovery Mechanism	"Swim to Cradle"	$ 350,000	Electro-Mechanical Device	$ 123,375	Articulated Mechanical Arm	$ 462,250
Launch Mechanism	"Swim Away"	$ -	Pressurized Gas Ejection	$ 660,250	Pressurized Gas Ejection	$ 660,250
UUV Re-charging Mechanism	Wet Cable Connection, UUV Stowed	$ 21,000	Dry Cable Connection, UUV Stowed	$ 18,425	Dry Cable Connection, UUV Stowed	$ 18,425
UUV Stowage System	Mechanical Locks	$ 78,000	Sealed/Dry Compartment in Tube	$ 32,550	Sealed/Dry Compartment in Tube	$ 32,550
L&R Control System Architecture	Portable, Plug-in Control Hardware/ Software	$ 25,855	Portable, Plug-in Control Hardware/ Software	$ 25,855	Portable, Plug-in Control Hardware/ Software	$ 25,855
Short-Range RF Communications	Underwater Radio Waves	$ 14,325	Underwater Radio Waves	$ 14,325	Underwater Radio Waves	$ 14,325
Acoustic Homing Communications	Acoustic Homing Beacon	$ 15,025	Acoustic Homing Beacon	$ 15,025	Acoustic Homing Beacon	$ 15,025
	Total:	**$ 2,116,955**	Total:	**$ 13,467,555**	Total:	**$ 7,120,680**

	Alternative 3 – Remote Vehicle		Alternative 4 – Performance Option	
	Technology Option	Cost	Technology Option	Cost
Support Structure	Titanium	$ 12,577,750	Composite	$ 5,892,000
Recovery Mechanism	Tethered Remote Vehicle (ROV)	$ 204,250	Electro-Mechanical Device	$ 123,375
Launch Mechanism	Pressurized Gas Ejection	$ 660,250	Electro-Mechanical Device	$ 172,375
UUV Re-charging Mechanism	Dry Cable Connection, UUV Stowed	$ 18,425	Inductive Charging (Touch Pad) UUV Stowed	$ 13,625
UUV Stowage System	Sealed/Dry Compartment in Tube	$ 32,550	Magnetic Lock	$ 36,300
L&R Control System Architecture	Portable, Plug-in Control Hardware/Software	$ 25,855	Portable, Plug-in Control Hardware/ Software	$ 25,855
Short-Range RF Communications	Underwater Radio Waves	$ 14,325	Underwater Radio Waves	$ 14,325
Acoustic Homing Communications	Acoustic Homing Beacon	$ 15,025	Acoustic Homing Beacon	$ 15,025
	Total:	**$ 13,548,430**	Total:	**$ 6,292,880**

b. Operations and Sustainment Costs

Operational and Sustainment costs were established for the fielded conceptual systems based on the assumptions provided at the bottom of Table 12. These assumptions identified the number of LRSs that will be fielded for each concept alternative, when they would be fielded with respect to a baseline fiscal year (FY BASE) and when they would be maintained by fiscal year. Minor maintenance cycles were identified as "PM" (Preventative Maintenance) with major maintenance identified as "OVHL" (Overhaul) or Upgrade. Time between maintenance was assigned by team members based on existing submarine operating cycles and the degree of maintenance considered necessary for the different types of components. Neither Disposal nor Salvage costs were considered as all concept alternatives were considered to be identical in these respects.

As costs for each alternative concept provided in Table 12 were identified in future year dollars, standardization was conducted to determine single dollar value costs for each concept alternative in present year dollars. Using OMB Circular A-94, a discount factor of 1.7% was applied to give the present year dollar costs, as given in Table 13.

Table 12 – Operations and Sustainment Costs for Life Cycle of each Alternative w/o Present Value Discount Factors Applied

	Acq - INCR1	PM	PM	PM	Ovhl/ PM	PM	PM	Acq- INCR2	Upgrade (6)	PM	PM	PM	Ovhl/ PM	PM
Alternative	FY Base	FY+2	FY+3	FY+4	FY+6	FY+8	FY+9	FY+10	FY+10	FY+12	FY+13	FY+14	FY+16	FY+18
Baseline (1)(4)	6.9	0.14		0.14	1.04	0.14		6.9	6	0.28		0.28	2.08	0.28
ALT-1 (2)(5)	27.4		0.55		0.55		0.55	27.4	2		1.1		1.1	
ALT-2 (3)(5)(7)	18.8		0.3		0.3		0.3	22.2	2		0.74		0.74	
ALT-3 (2)(5)	27.6		0.55		0.55		0.55	27.6	2		1.1		1.1	
ALT-4 (3)(5)(7)	17		0.26		0.26		0.26	19.5	2		0.65		0.65	

(1) 3 units bought for INCR 1 and 3 additional units bought for INCR 2
(2) 2 units bought for INCR 1 and 2 additional units bought for INCR 2
(3) 2 units bought for INCR 1 and 3 additional units bought for INCR 2
(4) Baseline unit get PM (2% Acq) every 24M and OVHL (15% Acq) every 3rd maintenance action
(5) ALTs unit get PM (2% Acq) every 36M
(6) INCR 1 units get upgrade at 10 years ($2M/Unit for Baseline, $1M/Unit for ALTs)
(7) Initial capital outlay of $4M for carbon fiber molds

Table 13 – Operations and Sustainment Costs for Life Cycle of each Alternative with Present Value Discount Factors Applied

Calculate Net Present Value in Current Year Dollars (1.7% Discount Rate per OMB A-94, Dec. 2010 for 20 yr life)

	Acq - INCR1	PM	PM	PM	Ovhl/ PM	PM	PM	Acq- INCR2	Upgrade	PM	PM	PM	Ovhl/ PM	PM	PM	In Present Yr Dollars ($M)
Alternative	FY Base	FY+2	FY+3	FY+4	FY+6	FY+8	FY+9	FY+10	FY+10	FY+12	FY+13	FY+14	FY+16	FY+18	FY+19	
Baseline	6.9	0.135		0.131	0.94	0.122		5.82961	5.0692268	0.229		0.221	1.588	0.207		21.4
ALT-1	27.4		0.523		0.497		0.473	23.1495	1.6897423		0.884		0.84		0.799	56.3
ALT-2	18.8		0.285		0.271		0.258	18.7561	1.6897423		0.594		0.565		0.537	41.8
ALT-3	27.6		0.523		0.497		0.473	23.3184	1.6897423		0.884		0.84		0.799	56.6
ALT-4	17		0.247		0.235		0.223	16.475	1.6897423		0.522		0.496		0.472	37.4

c. Indirect Costs

Due to different manufacturing processes between metallic (carbon steel and titanium) structures and composite (carbon fiber) structures, manufacturing costs were examined. Each metallic structure requires forming, machining, welding and non-destructive testing of the raw materials to create the final cylindrical structure. Although process improvements and "learning" may improve the manufacture process over the long run, the relatively small overall number of units required in a single fiscal year was considered to cancel out any long-term cost benefits in manufacturing. As shown in Appendix C tables, labor costs to manufacture each metallic structure were considered static and, based on similar work performed in public shipyards, estimated to take 250 Man Days at a labor rate of $680/Man Day, or $170K per structure.

Composite (carbon fiber) structures require molds and manufacturing processes such as compressive molding, to fabricate the parts necessary to create the structure. Molds for the compressive molding process are typically manufactured from a lightweight metal, such as aluminum, and are reusable. Initial manufacturing costs for the molds must be considered in the overall life-cycle costs of composite structures.

The cylindrical structure for the LRS would be designed for simplicity and uniformity throughout, using various circular and truss segments which would be mechanically fastened together. The Capstone team estimated that twenty (20) separate molds would be required to fabricate the composite structure. Using a known price of $7.5K for 4' x 12' x 2" aluminum plate and an estimated volume of 1500 in^3 per mold, the raw material costs for the molds was estimated at $600K. Using machining, tooling, maintenance, rental of presses and profit estimates of 250 Man Days per mold at a labor rate of $680/Man Day, the cost per mold equated to $170K. Therefore, the total estimated cost to manufacture, maintain and use the molds was $4M. This capital outlay cost was added to the carbon fiber alternatives when determining life-cycle costs.

After accounting for the initial costs of molds, the Capstone team determined that fabrication costs for the carbon fiber structures were comparable to fabrication costs for metallic structures. Preparation times and compression times for the molding process are similar to forming, machining and welding times for metallic structures. Both processes require skilled mechanics. Assembly times for carbon fiber structures were considered negligible. As such, manufacture of each carbon fiber structure was estimated to take 250 Man Days at a labor rate of $680/Man Day, or $170K per structure.

All other indirect costs such as training, specifications, facilities, and other logistical concerns were not specifically discussed above nor broken out as these costs were not considered significantly different for any of the alternatives. However, these costs were factored in and considered when preparing the costs for engineering, design, program management, material, and spare parts. The worksheets for all related cost estimates are provided in Appendix C – Cost Analysis Worksheets.

4. Cost Sensitivity Analysis

Titanium Discussion

Much of the titanium produced today goes into the manufacture of aircraft engine parts and structural components. Titanium dioxide is used in paints, paper and plastics and other products. Titanium has also become indispensible in the marine industry because of it corrosion resistant properties in saltwater. Wall thickness of titanium structural components may be reduced because of superior strength qualities and corrosion allowance. It is difficult to predict future prices of titanium but, based on current supply and anticipated demand, prices will likely increase in the future as China and India increases industrial demand for titanium materials. Figure 41 shows historical prices since 2005 that show a downward trend in price from 2005 to 2009 as the United States eliminated the remaining strategic Cold War government stockpiles [Seong, 2009]. The current price of titanium raw material bars and plates is approximately $7/lb and has increased slightly since 2009.

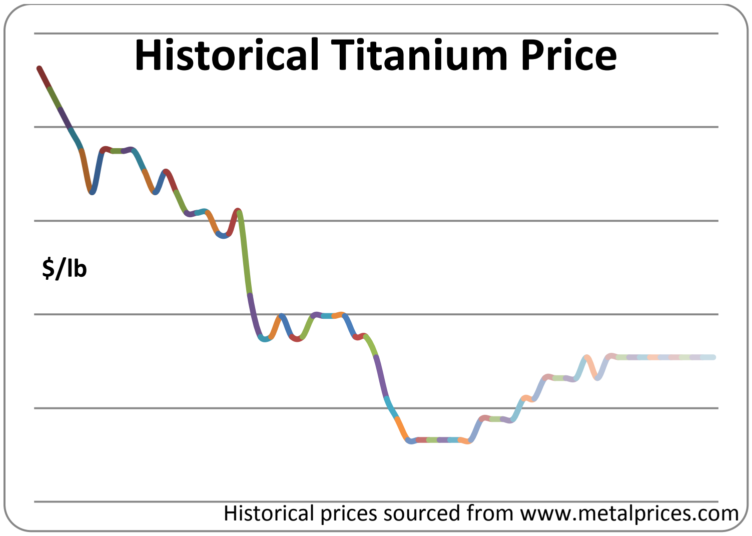


Figure 41 – Cost Comparisons Showing Varying Titanium Prices

The costs of the two alternatives containing titanium were approximately $13.5M, almost twice the next lower cost alternative that used a carbon fiber composite structure and six times the cost of the carbon steel alternative. A continued upward trend of price would likely make the titanium option much less appealing. Table 14 below provides a comparison of ALT-3 with varying costs of titanium and the differences from the lower cost alternatives. The current differences in cost of the lower cost options are significant and if the cost of titanium rises, the cost gap becomes increasingly excessive.

Table 14 – Cost Differences of ALT-3 with Baseline and ALT-4 Configurations

Titanium $/lb	ALT - 3 (with varying titanium costs)	Cost Difference from Baseline	Cost Difference from ALT-4
$ 8	$ 14,733,945	$ 12,616,990	$ 8,441,065
$ 10	$ 18,174,762	$ 16,057,807	$ 11,881,882
$ 11	$ 19,895,170	$ 17,778,215	$ 13,602,290
$ 14	$ 25,056,394	$ 22,939,439	$ 18,763,514
$ 19	$ 33,658,435	$ 31,541,480	$ 27,365,555

Carbon fiber composite is a strong, lightweight material that is at least five times as strong as steel and weighs about two-thirds less. Carbon fiber composite is composed of very thin strands of carbon, which are twisted and woven together and then laid over a mold and coated with resin to form a permanent shape. Carbon fiber composite technology has become a viable alternative material in the last fifteen years due to the raw material price per pound drop from around $150 to about $8 - $10. [Zoltec, 2011] As more industries explore the use of carbon fiber composites in their products, the price per pound should remain relatively stable if not decline. The analysis for the LRS Carbon Fiber Support Structure was based on a raw material cost of $8/lb, which resulted in an approximate $9M total cost for the first unit (factoring in $2M capital costs for manufacture of molds) and approximately $7M for each successive unit. Table 15 compares the differences in varying Carbon Fiber price per pound against the baseline alternative cost. Currently the raw material cost of $8/lb is roughly twice the baseline alternative cost. As the price per pound comes down, the cost difference becomes more of a desirable alternative.

When comparing the cost of Carbon Fiber against Alternative 3 (Titanium Option), Carbon Fiber is already a preferred choice when only considering cost. Table 16 compares the cost of Alternative 3 using Carbon Fiber vice Titanium for the support structure. The cost difference at the current raw material $8/lb estimate of carbon fiber material is $7.7M. This difference becomes significantly larger if the cost of carbon fiber composite comes down. The future trend for carbon fiber demand is expected to increase at a constant rate through 2013 [Zoltec, 2011] which could mean that lower costs are realized.

Table 15 – Cost Differences of ALT-4 with Baseline Configuration

Carbon Fiber $/lb	ALT-4 (with varying carbon fiber costs)	Cost Difference from Baseline
$ 4	$ 3,119,247	$ 1,002,292
$ 6	$ 4,478,431	$ 2,361,476
$ 8	$ 5,837,615	$ 3,720,660
$ 10	$ 7,196,798	$ 5,079,843
$ 14	$ 9,915,166	$ 7,798,211

Table 16 – Cost Differences of ALT-4 with ALT-3 Configuration

Carbon Fiber $/lb	ALT-4 (with varying carbon fiber costs)	Cost Difference from ALT-3
$ 4	$ 3,119,247	$ 10,429,183
$ 6	$ 4,478,431	$ 9,069,999
$ 8	$ 5,837,615	$ 7,710,815
$ 10	$ 7,196,798	$ 6,351,632
$ 14	$ 9,915,166	$ 3,633,264

5. Cost Analysis Results

Table 17 provides a summary of total costs for operations and sustainment for a life cycle of each alternative configuration analyzed. Because of anticipated reliability differences for each alternative, the alternatives that used superior structural materials would require fewer LRS units. Currently, the plan was for there to be two units for the east coast and two units for the west coast available at any time. Of the alternatives, titanium was considered the superior material; therefore, our acquisition plan is to purchase a total of only four units over two increments to accommodate the plan for two units on each coast. ALT-1 & ALT-3 both use titanium for the structure. Total cost for ALT-1 which included life cycle costs is $56.3 M and ALT-3 is $56.6M. These were the highest cost alternatives even with only acquiring four total units mainly because of the high costs of titanium used in the support structure.

ALT-2 and ALT-4 were the next highest cost alternatives and are composed of carbon fiber composite for the support structure. The acquisition plans for these alternatives included the purchase of five total units, two units at increment one and an additional three at increment two. The additional unit accounted for possible reduction in performance of one of the original units. Total costs for ALT-2 were $41.8M and ALT-4 $37.4M.

The baseline alternative was the lowest cost alternative even with the acquisition of six units which are required because of the inferior carbon steel material has a lower anticipated reliability. The total costs for baseline alternative is $21.4M. If costs were the only factor considered, the baseline alternative would be the natural recommendation since it is at least 50% less than the next higher alternative cost. But total cost would not be the only factor and will be part of the larger decision-making process to arrive at a recommended solution.

Table 17 – Total Life-Cycle Costs for Each Conceptual Alternative

Alternative	In Present Yr Dollars ($M)
Baseline	21.4
ALT-1	56.3
ALT-2	41.8
ALT-3	56.6
ALT-4	37.4

C. PERFORMANCE MODELING AND SIMULATION

1. Background

The baseline and four concept alternatives identified in Table 7 where modeled using a simulation software package known as ExtendSIM®. Modeling captured the performance of each alternative's four primary functions: Launch, Recovery, Maintain and Replenish. The ExtendSIM® modeling provided a means to evaluate each concept's anticipated behavior in operational conditions. Modeling parameters are unique for each concept alternative and were derived by evaluating the component composition of each alternative.

To construct the models and simulate operational conditions it was necessary to define various assumptions for operation. The weather assumptions in Table 18 were applied for launch and recovery models and were held constant for all simulation runs. When considering success for launch or recovery it was defined as the ability to launch or recover a UUV without being detected by a threat and without damaging the host platform, UUV or LRS. Being detected or causing any damage was considered a failed launch.

Table 18 - Weather Condition Likelihood

Weather	Probabilities
Fair	85%
Moderate	10%
Poor	5%

2. Evaluation Measures for Concept Alternatives

Each of the four models, Launch, Recovery, Maintain and Replenish were simulated 1000 times, creating a database to assess the performance of each concept alternative. The concept alternative parameters identified in Table 19 were derived from subjective evaluation of the components expressed in Table 7 using technical knowledge of the team members and their experiences with the various technologies. When reasonable comparisons could be made by the team, rationale for the choices and tolerances are provided in Table 19 Notes.

Table 19 - Concept Alternative Modeling Parameters

Modeling Parameters					
Parameter	**Baseline**	**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**
Launch duration [minutes][1]	15±2.5	11.25±2.5	11.25±2.5	11.25±2.5	12.75±2.5
Recovery duration [minutes][2]	37.5±3.0	25.5±3.0	30.0±3.0	27.0±3.0	25.5±3.0
Successful Launch/Recovery[3, 6]	92.00%	96.00%	94.00%	95.00%	96.00%
Communication Success	98.50%	98.90%	99.50%	99.00%	98.00%
Reliability[7]	96.80%	98.00%	97.30%	98.40%	98.40%
Diagnostic Success	98.50%	98.50%	98.50%	98.50%	98.50%
System Reconfiguration Success	98.90%	98.90%	98.90%	98.90%	98.90%
Mission Upload Success	99.00%	99.00%	99.00%	99.00%	99.00%
Recharging Success	99.00%	98.00%	98.00%	98.00%	97.00%
Replenishment Duration [hours][4]	45.6±5.7	45.54±0.66	45.54±0.66	45.54±0.66	43.71±1.89
Maintain Positioning Success	99.00%	99.00%	99.00%	99.00%	99.00%
UUV Successful Secured	99.00%	99.50%	99.50%	99.50%	99.20%
ISR Data Download Successful	99.80%	99.80%	99.80%	99.80%	99.80%
Maintain Duration [minutes]	15.0±2.5	12.0±3.0	12.0±3.0	12.0±3.0	11.0±2.5
Overall Total Cycle Time [hours][5]	46.73	46.35	46.35	46.35	44.53

Table 19 Notes

(1) Based on average time to load mission/launch VLS Weapon, SSN 688 Class. Weighting factors consider speed at which launch method allows UUV to "clear" submarine envelope.

(2) Based on average time to load mission/launch VLS Weapon, SSN 688 Class (time is doubled as a baseline for recovery). Weighting factors include distance required to recover and if recovery equipment can operate in a 360° field vice limited direction.

(3) Based on success of torpedo test launches for SSN 688 Class. Does not account for UUV failure or system reliability (covered elsewhere). Weighting factors considers speed, movement of submarine, autonomy of launch/recovery (navigation error of UUV).

(4) Objective charging time assumes 500kWh charge required (energy capacity for the "Standard" Large Vehicle Class UUV) using largest available submarine source (440 VAC, 30 Amps). For wet conductive charge, assume 95% efficiency plus factor for corrosion damage, water leakage. For dry charge, assume 6 hours to dry stowage compartment and 95% to 98% efficiency. For wet inductive charging, assume 80% to 90% efficiency.

(5) Based on A_O factor for a SSN 688 Class Torpedo Tube Launch System. Weighing factors consider the complexity of the technology and environment (wet vs. dry).

(6) Factor of noise at launch/recovery, speed of launch recovery, security of equipment when stowed.

(7) Measures robustness of the equipment. The likelihood of failure per 1000 cycles. Increased moving parts, system complexity and corrosion of carbon steel would negatively affect system. Carbon fiber is more prone to shear stress damage and impact damage. Titanium would offer corrosion resistance and reduction in weight with significant strength advantages. A gas launch system creates additional stresses which could potentially induce component failure. Redundancy of ROV is advantageous. Single point failures are bad (technology that requires excessive power, failure to dry the stowage compartment, etc).

3. Model Descriptions and Results

a. Model Description

To provide a realistic and germane mission scenario to the model, Operational Situation No. 1 (OPSIT #1) proposed the use of the submarine launched Large Vehicle Class UUVs to counter efforts by a foreign power to choke off oil exports through a geographically critical area such as the Strait of Hormuz. Figure 42 provides a visual depiction of the Strait of Hormuz.

Figure 42 – Depiction of Strait of Hormuz

At its narrowest point, the Strait of Hormuz is 21 miles wide, and the shipping lanes consist of two-mile wide channels for inbound and outbound tanker traffic, as well as a two-mile wide buffer zone. The majority of oil exported through the Strait of Hormuz travels to Asia, the United States and Western Europe. In 2007, an average of 15 crude oil tankers passed through the Strait of Hormuz daily, along with tankers carrying other petroleum products and liquefied natural gas (LNG).

Foreign action to block transit though this area would result in oil shortages, increase the price of oil and potentially lead to world-wide financial crisis. Foreign governments in this area of the world have been unstable and consistently have taken an adversarial posture towards United States interests. Persistent-ISR missions by multiple UUVs in this high sea traffic area would enable US and allied Intelligence interests to react quickly to challenges by an enemy force with minimal risk to US submarines. Success of this mission requires the success of all four functions: Launch, Recovery, Maintain and Replenish. Failure to satisfy all four functions would compromise the OPSIT.

b. Modeling and Simulation Results

All four functions, Launch, Recovery, Maintain and Replenish, were successfully modeled using the parameters specified per Table 19. The ExtendSIM® models used for simulation can be found in Appendix D. Data derived from each of the models was analyzed with descriptive statistics to evaluate the performance of each alternative. The raw data from each model can be found in its respective section of Appendix D. The critical performance results of concern were the likelihood of success for each of the four functions and their average operational time as reported per Table 20. The concept alternatives where then ranked in accordance to performance from best to worst in Table 21.

In respect to OPSIT #1, mission success was defined as the success of all four functions: Launch, Recovery, Maintain and Replenish. When evaluating the results, a concept alternative can only be as successful as the system's reliability to successfully perform all four functions when pertaining to OPSIT #1. The likelihood of success for OPSIT #1 and the total operational time for each alternative is identified in Table 20.

Table 20 - Model Simulation Results

	Launch		Recovery		Maintain		Replenish		OPSIT#1	
	Success	Time [min]	Success	Time [min]	Success	Time [min]	Success	Time [hr]	System Reliability	Time [min]
Baseline	81.50%	14.97	81.00%	37.45	96.70%	15.07	93.60%	45.56	59.75%	2801.09
Alt 1	90.30%	11.25	88.70%	25.63	96.80%	12.04	93.00%	45.55	72.11%	2781.92
Alt 2	85.40%	11.25	86.60%	30.05	98.20%	11.99	94.30%	45.54	68.49%	2785.69
Alt 3	89.40%	11.33	87.70%	26.95	97.10%	12.22	92.40%	45.55	70.34%	2783.5
Alt 4	90.10%	12.84	87.20%	25.47	96.10%	10.98	91.10%	43.7	68.78%	2671.29

Table 21 - Ranked Alternative Performance

	Launch		Recovery		Maintain		Replenish		OPSIT#1	
	Success	Time	Success	Time	Success	Time	Success	Time	System Reliability	Time
Best	Alt 1	Alt 1	Alt 1	Alt 4	Alt 2	Alt 4	Alt 1	Alt 4	Alt 1	Alt 4
4	Alt 4	Alt 2	Alt 3	Alt 1	Alt 3	Alt 2	Alt 4	Alt 2	Alt 3	Alt 1
3	Alt 3	Alt 3	Alt 4	Alt 3	Alt 1	Alt 1	Alt 3	Alt 1	Alt 4	Alt 3
2	Alt 2	Alt 4	Alt 2	Alt 2	Base	Alt 3	Alt 2	Alt 3	Alt 2	Alt 2
Worst	Base	Base	Base	Base	Alt 4	Base	Base	Base	Base	Base

After review and analysis of the model simulation results of Table 20 it was observed that all concept alternatives significantly outperformed the baseline, which only resulted in a system reliability of 59.75%, compared to the more advanced alternatives, whose reliabilities ranged from 68.49% to 72.11%. The overall time to complete all four functions, Launch, Recover, Maintain and Replenish were negligible between the baseline and alternative LRS designs with times ranging from 2671 minutes to 2801 minutes. This was due to the relatively similar time required to successfully refuel the UUV which was grossly more time consuming in comparison to the time it took to complete launch, recovery or maintain functions.

c. Model and Simulation Conclusion

In an evaluation the model results on a purely performance perspective Table 21 ranked the baseline and all concept alternatives from best functional performance to worst functional performance. Alternative-1 proved to be the most reliable, 72.11%, while Alternative-4 proved to have the best time performance completing all functions in a total of 2671 minutes. Alternatives 1 and 4 dominated Alternatives 2, 3 and Baseline when compared to reliability and time performance per OPSIT #1 and, as such, from a performance standpoint, are considered the superior alternatives. However, without additional knowledge of the stakeholder value system or a weighting associated with reliability or speed, no single alternative was be down-selected purely on performance.

d. Launch & Recovery Sensitivity Analysis

A sensitivity analysis evaluated the baseline and design concepts sensitivity to variation in LRS component success and its effect on a successful launch and recovery. Simulations were conducted on all design models identified in Appendix D, varying the LRS reliability parameter by 5%, 10% and 15%. The simulations were successfully performed and the results are identified in Table 22.

Table 22 - Launch & Recovery Sensitivity

		Launch			Recovery		
	LRS Reliability Variable	**LRS Component Success**	**Launch Success**	**Sensitivity Launch/ Component Success**	**LRS Component Success**	**Recovery Success**	**Sensitivity Recovery/ Component Success**
Alt 1	98.00%	98.40%	90.30%	0.90	98.00%	88.70%	0.89
	93.00%	91.90%	84.90%		92.40%	83.10%	
	88.00%	87.10%	80.90%		88.60%	79.80%	
	83.00%	81.60%	75.00%		84.10%	76.40%	
Alt 2	97.33%	97.20%	85.40%	0.86	97.40%	86.60%	0.94
	92.33%	91.40%	81.10%		93.70%	82.50%	
	87.33%	87.00%	76.40%		87.80%	76.30%	
	82.33%	81.00%	71.70%		81.60%	71.80%	
Alt 3	98.40%	99.20%	89.40%	0.76	98.60%	87.70%	0.89
	93.40%	93.40%	82.80%		93.00%	84.70%	
	88.40%	87.10%	79.50%		91.10%	81.20%	
	83.40%	82.10%	76.00%		82.40%	73.70%	
Alt 4	98.40%	98.00%	90.10%	0.95	98.50%	87.20%	0.79
	93.40%	94.10%	87.00%		94.10%	84.50%	
	88.40%	88.10%	81.60%		88.30%	79.00%	
	83.40%	83.40%	76.10%		86.60%	78.30%	
Baseline	96.80%	97.00%	81.50%	0.71	96.00%	81.00%	0.91
	91.80%	92.60%	78.10%		92.10%	77.50%	
	86.80%	87.20%	74.30%		85.00%	70.70%	
	81.80%	81.70%	70.60%		82.90%	69.30%	

The results of Table 22 were plotted to provide a visual representation of the data and are provided in Figure 43 and Figure 44. When evaluating the data, the lower the slope, the less sensitive an alternative is to the LRS component reliability changes. Utilizing this data, it was observed that Alternative-4 exhibited the greatest sensitivity, 0.95, to LRS component changes effecting reliability during launch, but exhibited the least sensitivity during recovery, 0.79.

The sensitivity slopes identified in Table 22 defined the predicted effects of varying LRS reliability in relation to successful launch and recovery functions, where success was defined as a launch or recovery that is not detected and does not cause any damage to the UUV or Host Platform. This information was used when alternative LRS components were evaluated for re-design of particular concept alternatives and how it will affect functional performance. The graphical plots Figure 43 and Figure 44 identified minimal LRS component reliability necessary to satisfy operation threshold and objective requirements.

In conclusion, assuming that the LRS component reliability was 100%, it could extrapolated from the sensitivity slopes the best likelihood of launch and recovery success is for each alternative. Table 23 provides the probability of success assuming 100% LRS reliability. If the probability of success identified in Table 23 is not acceptable, then changes to design and other system components must be made to improve the likelihood of success.

Table 23 - Extrapolated 100% LRS Reliability

	Launch	**Recovery**
Alt 1	92.03%	90.18%
Alt 2	87.99%	88.60%
Alt 3	89.14%	89.57%
Alt 4	92.37%	88.63%
Baseline	83.49%	84.63%

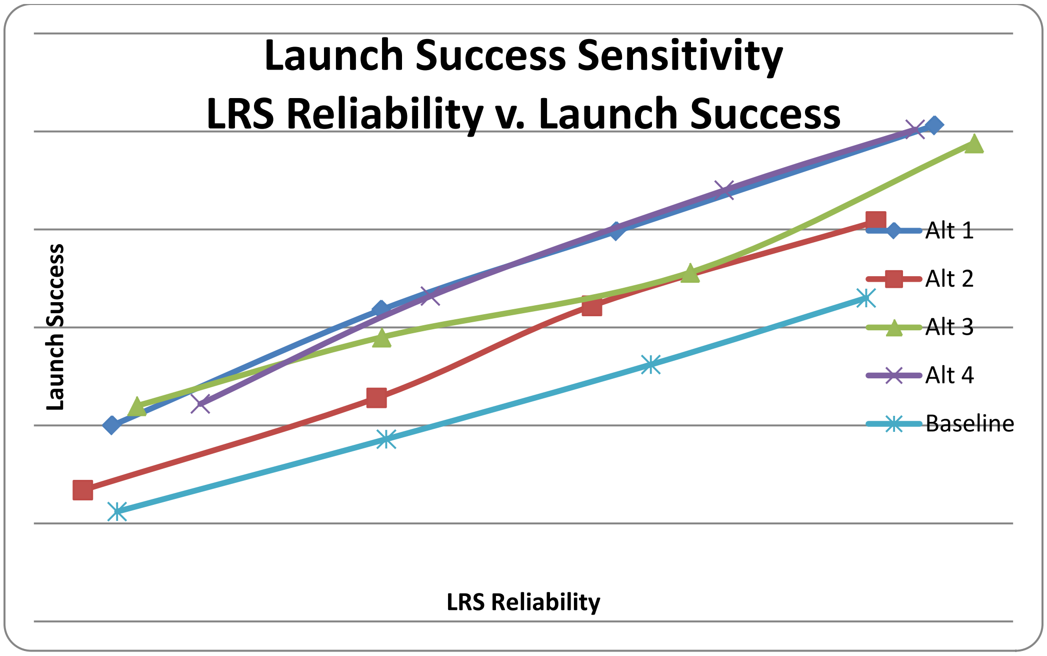


Figure 43 - Launch Sensitivity

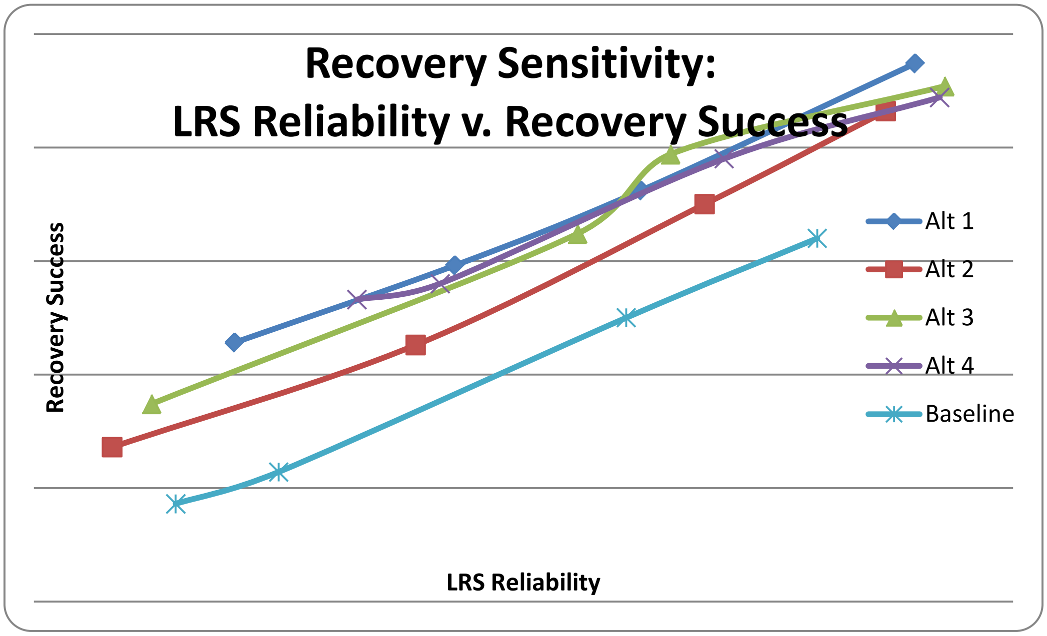


Figure 44 - Recovery Sensitivity

IV. DETAIL DESIGN CONSIDERATIONS

A. DESIGN ASSESSMENT

1. Background

Design assessment took a qualitative approach to evaluate each conceptual alternative design considerations in support of a final recommendation. Equipment and hardware/software interfaces were evaluated to ensure that cohesion, coupling and connectivity are at a level necessary to exhibit emergence of system functions. System reliability was analyzed to determine if redundancy was at the correct levels to provide maximum system availability at minimum cost. Safety and usability were assessed to examine concept alternatives with respect to risks imposed on the host submarines and users as well as potential mitigations which could improve overall safe operation. Logistics and test strategies were envisioned to help validate the acquisition and long term soundness of the concept alternatives. Finally, decision analysis applied a process to the results of the modeling and analysis to recommend an approach to a final concept alternative.

2. Interface Analysis

Interface analysis compared the inputs and outputs of the LRS with corresponding connections to internal and external performers for the overall system. The analysis assesses risks for the physical, power, communications and system level interfaces. Each input or output to the LRS was traced to the part of the overall system that provides that input or output. Table 24 provides a summary of the interfaces of the LRS, and between the LRS, UUV and host submarine.

Interface	*Physical*	*Power*	*Communications*	*Dimensional*
LRS Launcher Mechanism to UUV		x	x	x
LRS Launcher Mechanism to LRS Control Station	x	x	x	
LRS Control Station to Host Submarine	x	x	x	x
LRS Control Station to Submarine Crew				x
LRS Launcher Mechanism to Payload Tube	x			x
LRS Control Station to LRS Operator	x			
LRS Recovery Mechanism to UUV		x	x	x

Table 24 – System Internal and External Interfaces

a. Interface Risks

Risks associated with the four (4) categories of interfaces are detailed below:

Dimensional:

- A securing/release mechanism sized for a persistent-ISR UUV should have an ability to accommodate a smaller UUV. Since the size of a smaller UUV was not defined, there is a risk with accommodating such a vehicle. Incorporation of universal mechanisms that would accommodate various sized UUV's is required.
- The host ship control room or torpedo room must accommodate the physical dimensions of the LRS control station. Because of limited space availability, there would be a risk of a non-ergonomic installation because of limited locations available for installation. A study of availability will be required to determine optimal location for installing the LRS Control Station. It might be necessary to integrate LRS control into existing workstations.

- The LRS Control Station must be located within a specified visual range of the Officer of the Deck (OOD) to support real-time continuity with host submarine operations. There was a risk to the launch/recovery if control station operators did not have visual observance in the control room environment.
- The launch and retrieval mechanisms must fit within the length and diameter of the payload tube without interference to the payload tube hatch. A risk of improper tolerances could lead to vibration or misalignment of the launch/retrieval mechanism. The launch/retrieval mechanism must be designed to accommodate vibration and other shipboard motions by incorporation of standard motion dampening mounts.

<u>Power:</u>

- Wetted power distribution plugs must provide a watertight connection with UUV power receptacle and provide required electrical supply. The risk of a non-watertight seal results in poor reliability and slow power transfer rate which could jeopardize a mission and fail to meet the threshold replenishment time. Design of watertight connections should leverage off proven designs currently used in submarine sonar or vertical launch systems.
- A power cable will supply electrical and battery power to the UUV for activation of actuators. Because of the risk of host ship lacking enough reserve power to accommodate launcher power requirements, a load analysis should be performed to ensure host ship's ability to power the LRS.

<u>Communications:</u>

- The data cable connection from the LRS to UUV must provide a watertight mate and provide the required data transfer rate. The risk of a non-watertight seal resulted in poor reliability and slow data transfer rate which could jeopardize a mission and fail to meet the threshold launch time. Design of watertight connections should leverage off proven designs currently used in submarine sonar and vertical launch systems.

- The noise level in the control room should not exceed a specified level due to operating equipment. There is a risk of misunderstanding commands between the control station operator and OOD if noise levels from the control station exceed specified levels. Design of the control workstation must be similar to other workstations with regard to noise.
- The acoustic and Radio Frequency (RF) communications features of the LRS must have signal strength to clearly transmit information from the LRS to the UUV to support the UUV recovery process. Signal transmitters should utilize commercially successful systems proven to propagate in various water conditions, line-of-sight situations and background noise levels without jeopardizing submarine stealth.

Physical:

- Shock qualified restraining devices must hold down workstation and associated cables piping, etc. There would be a risk of unrestrained objects/equipment during a shock event which could injure or jeopardize the crew or ship. The required grade shock analysis and testing must be performed during design of LRS components.
- The interface between operator and control station should provide an ergonomic input device. A risk of repetitive stress injury could occur without an ergonomic design. Use of latest ergonomic design standards is required for us in design of input devices.

b. Software Strategy

Overview of Required Work

Requirements and Constraints on the System and Software to be developed:

- The LRS would be fully integrated into an existing submarine hull and control room. The software must accommodate an interface between the LRS control station and ship's communication system, as well as the LRS control station and the launch/recover mechanism. The software must function as a communications link and data transfer station between the ship, LRS control station, LRS launch/recover mechanism and the UUV. The software will be required to interface with and manipulate the launch/recovery mechanism. The user at the LRS control station will be using a dell laptop and operate the system through a GUI.

Requirements and constraints on project documentation:

- The software GUI would be used by enlisted sailors under possibly stressful conditions. Documentation should be simply stated and well organized.

Position of the project in the system life cycle:

- The software would be developed to support software specific Developmental Testing and software/hardware integration into the LRS for its Developmental Testing, and be supported and maintained throughout all Operational Testing and service life of the LRS.
- Constraints from Program/Acquisition Strategy - There were no constraints from the acquisition strategy. The software development process conformed to the acquisition schedule to support DT and OT.

Requirements and constraints on project schedules and resources:

- The software development process would begin early enough to not invoke risk to software reliability in order to meet the program testing schedule.

Other Requirements and Constraints:

- The software and all associated documentation shall be Distribution Statement D.

Plan for Performing Software Development Activities.

Software Development Process:

- The software code and supporting documentation should be developed for the specific architecture of each viable system concept to support a fully operational prototype of each concept.

General Plans for Software Development:

Software development methods - Due to the early stage of development, there exists a potential for mixing and matching physical concepts as the design matures. As such, the supporting software will need to be interchangeable. Definition of the interfaces between each concept shall be identified at a global software level, and upheld as the development of the software code continues. Consistent format, headers, variable identification and declaration will be used throughout the software development phase. A consistent methodology will also be used in development of the algorithms for each module. Each module will be tied to a specific function from the project's functional analysis. This development scheme allows for the maximum flexibility when the final configuration of the physical concept was defined.

Standards for software products - Consistent format, headers, variable identification and declaration will be used throughout the software development phase. A consistent methodology will also be used in development of the algorithms for each module.

Reusable software products - Due to the simplistic nature of the functions the software is required to fulfill and the desire for maximum commonality between modules for each concept, reuse of existing software will not be enacted. Reformatting existing software to make it compatible with each of the concepts will not be an efficient use of time.

Handling of critical requirements - The design and functions do not contain any Fly-by-Wire aspects. As only one penetration for power and data is required, there are no safety critical aspects that relate to software. No software modules would operate components in the SUBSAFE boundary.

Computer hardware resource utilization - The development would take place using standard desktop computer hardware. No special hardware requirements are needed for the development of these modules.

Recording rationale - As each module is tested, a full data log will be kept, recording inputs, outputs, total run time and error records.

Access for acquirer review - The code would be the property of the Department of Defense and be available for review at any time.

Plans for performing detailed software development activities

Project Planning and Oversight - The lead software engineer would prepare an outline of the modules to be developed and link the development timeframe of that outline to the project design schedule. The software development must sync up with key design milestones. The lead software engineer would provide weekly status updates to the program manager regarding the adherence to the project design schedule.

Establishing a software development environment - Software developers would be co-located and have ready access to the pre-defined functional decomposition and component selection matrix as well diagrams of the component physical architecture and identified interfaces.

System Requirements Analysis - Stakeholders identified their top level requirements for the project. These requirements have been consolidated and formed the basis for the functional architecture.

System Design - The physical architecture was defined and populated with components from the component selection matrix. Different components of the physical architecture were mapped to specific functions. The architecture would not change for the duration of the project without redefining the scope of the project.

Software Requirements Analysis - From the functional decomposition and component matrix, the project will identify any function that requires the aid of software. Each concept required its own software modules based on specific components of that concept. Each module would be written with the understanding that concepts could swap components as the design matures. The software must be able to handle that adaption.

Software Design - Each module would be developed for a specific function and supporting component. Inputs and outputs would be determined by the interfaces between the components.

Software Implementation and Unit Testing - As the software development must match the project development milestones, implementation and testing would be scheduled with ample time to address implementation issues. Because each module was developed for this project (no re-use of existing software), debugging can be accomplished with project specific inputs and environments. This would eliminate integration issues that would arise from software re-use. Each module would be tested with simulated inputs before software/software integration. Once each module passed individual testing, modules that need to be combined before hardware/software integration would be tested with simulated inputs.

Unit Integration and Testing - Once a series of modules were combined and successfully tested, hardware/software integration would be accomplished prior to component integration. This would allow for simulated inputs, based on the recognized interfaces, to be used in individual component testing. Any bugs would be fixed prior to component integration. The simulated inputs would mimic actual inputs as close as possible.

System Qualification Testing - The software would be tested in each component prior to component to component integration. The software qualification testing would be considered complete if the integrated prototype met requirements satisfied by software implementation.

Preparing for Software Use - Each member of the design development team or operating crew would be trained on the proper use of the software. Manuals with instructions and troubleshooting guides are to be provided to each trainee as well as made available with each workstation, which operates the software.

Software Configuration Management - An outline of variable usage, headers, comments, and language is provided to each software developer. In addition, at weekly meetings, examples of current code were displayed for all developers to verify that their efforts mimic the displayed code format. Each developer shall be individually responsible for his own version control of the software. Once he has completed a module, it would be turned over to the lead software engineer for archive purposes and is stored until individual or integrated testing is to take place. Once software has been successfully integrated into a component, it will have a unique version number identifying it as a working software package. A standard revision system would be levied on the software development efforts. Each updated version to a software/hardware integrated component would follow the revision format. The lead software engineer would be responsible for integration of the software package into the hardware component.

3. Reliability Analysis

The LRS has a robust reliability strategy that meets current DOD requirements. [OSD ETDM, 2011] Reliability is a system engineering discipline and the requisite actions and activities are embedded in the tasks listed in the integrated master schedule. For example, reliability strategies were integrated as part of the overarching design review and test and evaluation process. Reliability program success will be judged by meeting objectives for Mean Time between Failures (MBTF) and Mean Time between Operational Mission Failures (MTBOMF), which supports system Operational Availability.

Design for reliability methodologies were planned throughout the design selection and development process. These include:

- Block Diagrams and Predictions
- Failure Modes, Effects and Criticality Analysis (FMECA)

Block Diagrams and Predictions were planned to determine preferred system redundancies (e.g. dual power supplies, dual software routines, back-up control systems), and sparing requirements. During the concept exploration phase, initial reliability comparisons were made between the baseline model and the four identified alternatives. The output data from the ExtendSIM® model provided the early look reliability numbers of each top level function based on the percent success report from ExtendSIM®. Among the different concepts, the reliability of each top level function was compared as well as the overall concept reliability. At this stage of development, predicting or assigning reliability targets/values to any sub level functions cannot be done with any degree of fidelity. The formula for top level reliability analysis based on functional reliability is:

$$R_{\text{Total}} = (R_{\text{Launch}})*(R_{\text{Recovery}})*(R_{\text{Replenish}})*(R_{\text{Maintain}})$$

This concept is illustrated in Figure 45.

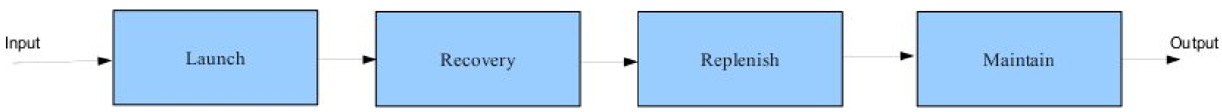


Figure 45 – Top-Level Reliability Diagram

The second reliability block diagram option, Figure 46, took advantage of the redundancy with electronic and software components, which comprise the majority of the "Replenish" and "Maintain" function components. Without a large volume or weight penalty, physical components of replenish and maintain were arranged to offer additional redundancy to the functions. The reliability advantage of this redundancy was represented in the reliability calculations such that a 0.90 reliability allocation to each replenish or maintain subsystem increase the combined reliability of replenish or maintain functions to 0.99, using the formula:

$$R = R_{\text{A}} + R_{\text{B}} - (R_{\text{A}} * R_{\text{B}})$$

This resulted in a combined replenish and maintain reliability of 0.99 * 0.99, or 0.98. While arranged in series, two functions with 0.90 reliability provide a combined reliability of

$$R_{\text{A}} * R_{\text{B}} = 0.9 * 0.9 = 0.81$$

Due to large reliability benefit of redundancy in these two systems, early integration of redundancy should be considered. The overall reliability of this system model is calculated with the equation:

$$R_{\text{Total}} = R_{\text{Launch}} * R_{\text{Recovery}} * [R_{\text{Replenish,a}} + R_{\text{Replenish,b}} - (R_{\text{Replenish,a}} * R_{\text{Replenish,b}})] *$$
$$[R_{\text{Maintain,a}} + R_{\text{Maintain,b}} - (R_{\text{Maintain,a}} * R_{\text{Maintain,b}})]$$

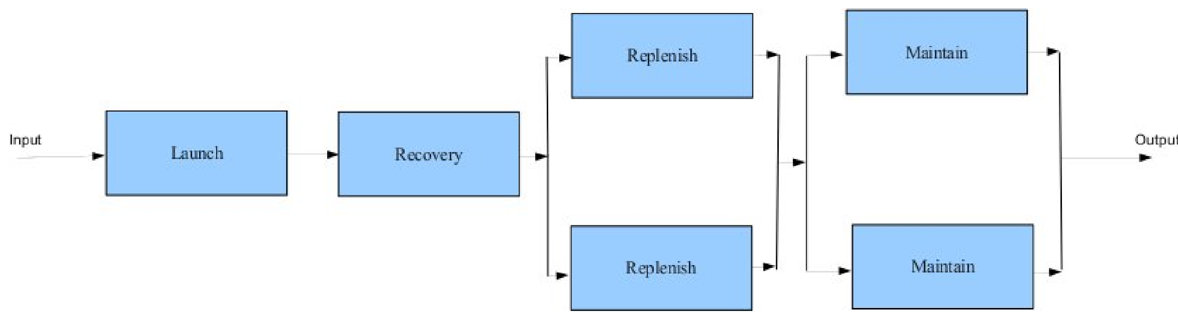


Figure 46 –Reliability Diagram with Redundancy

The third and most complex reliability block diagram arrangement, Figure 47, took advantage of a highly integrated system. For this arrangement, launch and recover were again in series, but replenish and maintain have redundancy amongst themselves (as in the second reliability block diagram concept) while performing simultaneous functions. For example, a diagnostic process could be run at the same time as replenishment. The reliability advantage of this redundancy was such that a 0.90 reliability allocation to replenish or maintain subsystems will again prove to be 0.99, but when these two functions are arranged in parallel, their combined reliability (replenish = 0.99 and maintain = 0.99) is 0.9999. The reliability was then expressed as:

$$R_{\text{Total}} = R_{\text{Launch}} * R_{\text{Recovery}} * [R_{\text{Replenish,ab}} + R_{\text{Maintain,ab}} - (R_{\text{Replenish,ab}} * R_{\text{Maintain,ab}})]$$

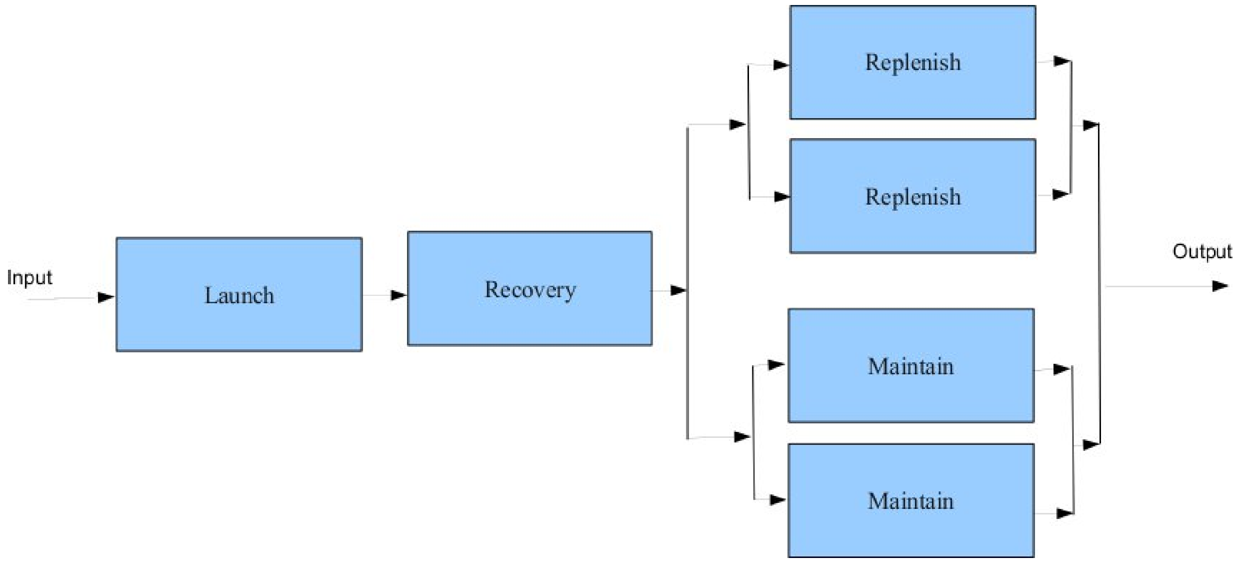


Figure 47 – Integrated System Reliability Block Diagram

A Failure Modes and Effects and Criticality Analysis (FMECA) were used to analyze the risks or weaknesses of different types of system components which could adversely affect the overall system reliability. This analysis used the requirements analysis, functional analysis, and requirements allocation as a starting point. The failure modes are identified, which includes the methodology by which the system fails to function (or a component fails to support the system functioning). The root causes were identified; (Does the hatch fail due to a sealing surface, or due a faulty fastener?) The effects of the failure were then determined, along with the detection methods, frequency and criticality. This data is used to recommend changes to the design, as well as the supportability requirements. The analysis would be planned for the design phase to minimize re-work. Table 25 identified potential failures, critical analysis and mitigations for LRS component packages.

Table 25 – Example Failure Modes Effects and Criticality Analysis

Functional Failure	Systems Failures	Consequence	Mitigations / Design Recommendations
Launch System fails to launch UUV when command is given	Launch System software fails to initiate system.	UUV remains in submarine in dormant state. UUV is not available for mission.	Mechanical Backup launching system or Manual Over-ride. Redundant Software Systems
Stowage and Support Structure fails to securely stow the UUV	Support Structure Failure	UUV damage to ship Potential injury to crew Damage to UUV could preclude it being launched	Structural analysis of failure points, additional support to UUV Use robust structural components
	Stowage Mechanism Failures	Loose UUV falls and damages submarine injures crew or damages UUV	Backup mechanisms for secure stowage Consider independent mechanical/electrical systems
Failure to collect UUV payload data	Communications systems failure	UUV data collected is lost and not available for subsequent missions. Potential enemy recovery of classified data and technology.	Redundant communications methods.
	Mechanical recovery mechanisms fail to interface with UUV	Loss of UUV and collected data. UUV damages ship. No ability to re-launch UUV for subsequent missions. Damage to intelligence if recovered by enemy	Design interface with backups Use remote or proximity vice direct interfaces
UUV control system fails	Control of UUV is lost as it approaches submarine	UUV damages submarine pressure and or non-pressure hull structure. UUV itself is damaged, causing the data collected not to be recoverable. This results in the loss of intelligence as well as the potential loss of the ability to re-launch UUV for subsequent missions.	Control System architecture must have robust design with safety analysis done. Redundant System to address failure of operating laptop with ability to port software onto a "standard laptop" if available.

4. Safety and Usability Analysis

A Failure Modes and Effects and Criticality Analysis (FMECA) addressed the Safety Risks to the submarine and personnel associated with the launch and recovery of Large Vehicle Class UUVs. Among the risks addressed:

- Implodable Volumes – Defined as “any pressure housing containing a non-compensated compressible volume at a pressure below the external sea pressure (at any depth down to the maximum operating depth) which had the potential to collapse.” Externally mounted lights, gauges, bottles/flasks, spheres/tanks and beacons are examples of implodable items. The LRS shall minimize implodable volumes. Structural materials with sealed internal cavities (Carbon Steel, Titanium) could pose issues as well as Gas Generator Launch components with gas storage flasks.
- Collision - The consequences of a large UUV crashing into the submarine structure are severe, with the potential for damage to the submarine hull, causing an uncontrollable flooding casualty. The risk to the submarine is minimized during the time that the UUV is deployed and being recovered by the control system. Systems that control the UUV approach to the submarine such as an EMP Attraction Device or ROVs would be favored over systems where the UUV must navigate to a docking location.
- Off-Gassing Hazards - The UUV power systems have the potential to release explosive gases (e.g. hydrogen and oxygen). Sealed and dry stowage systems may be more susceptible to the build-up of gases and must consider ventilation to support safe operation.
- System Installation and Removal - The stowage system will be designed to maximize the use of cranes and jigs for loading the UUV into its final launch position prior to the submarine’s deployment. The LRS would use of harnesses and jigs, to minimize the risk of physical injury to ships force when reloading the UUV into the submarine.

Lightweight composite structures that minimize equipment requirements and training would be preferred over heavier and rigid equipment.

- Underwater Explosion Risk – All internal and external components would be designed to meet MIL-STD-801 Grade B shock requirements to minimize the risk of injury in an underwater explosion event. Grade B shock means that the equipment will maintain structural integrity but not function. Communications and control system equipment must be designed for installation into the existing equipment racks. Outboard equipment must not come adrift and impact function and operation of other submarine components. Rigid metallic components and electrical components with limited mechanical parts would be desired to best resist shock events.

5. Test and Evaluation Strategy

The Test and Evaluation Strategy (TES) for the LRS provides an overview into the necessary testing at various stages of concept development. Specific strategy recommendations are provided as Appendix E.

The test strategy for all potential conceptual alternatives relies on Modeling and Simulation (M&S) during early development, component specific Demonstration Test and Evaluation (DT&E) performed by contractors with Government oversight and Operational Test and Evaluation (OT&E) performed on a fully integrated prototype model. In general, M&S and DT&E processes are considered relatively low risk. Many proposed component alternatives are technically mature and those which require laboratory development are based on demonstrated scientific principles. Demonstration testing of integrated mechanical system components, such as the launch, recovery, stowage and structural systems, using Large Vehicle Class UUV representative models is possible in Government laboratory facilities with minimal resource requirements. Demonstration testing of control and communication components can effectively be combined with operational testing as all component concepts are Commercial-Off-The-Shelf and/or currently in-service technologies.

Operational testing represents the highest level of program and performance risk for all anticipated concepts. As such, the test strategy recommends two (2) phases of OT&E to limit the testing time with in-service submarine resources. Phase I would test a fully integrated LRS prototype in a Virginia Payload Tube (VPT) model, using representative Large Vehicle Class UUV models. Testing would be accomplished at US Navy test tank facilities at Bethesda, MD and would focus on successful operation of a fully integrated system in a controlled environment. Upon satisfactory Phase I testing, environmentally realistic testing (Phase II) would be conducted using a target Large Vehicle Class UUV and a VA Class Block III submarine. Phase II testing would concentrate on vehicle deployment and recovery from a submerged and moving submarine and would assess the radiated noise from an operating system. Additionally, Phase II will address human factors and training of system users as well as integration and data flow problems between the UUV and the submarine via the LRS. Significant issues identified during Phase II testing would be analyzed for corrections not only during successive increments of the LRS, but also during successive builds of the VA Class submarines and commercial UUVs.

6. Logistics Strategy

As part of the preliminary and detailed design effort a logistics support, trade-off and maintainability analysis will be addressed. A level of repair analysis (LORA) will be done to identify what components may be repaired or replace at the operational (O-level), intermediate (I- Level), or depot maintenance level. Consistent with the current U.S Navy policy, a reliability centered maintenance (RCM) concept will be applied to minimize total ownership costs. In addition, the use of unique components would be minimized, specifically components required to be carried as on board repair parts (OBRP). The use of common components minimizes or eliminates the need for extra maintenance training. Components would be analyzed to determine which could be "swapped out" and repaired off hull vice shipboard. The issues and risks to be addressed in design development would include:

- Durability of the carbon fiber vice titanium or carbon steel structure.
- LRS structural material compatibility with existing host submarine operating environments and platform requirements.
- Preservation costs of high strength carbon steels.
- Identification of special training and certification requirements for technicians maintaining the LRS associated with, but not limited to; installation, preventative and scheduled maintenance, equipment, and facilities necessary to accommodate maintenance.
- The use of commonality, open system architecture and interfaces to optimize logistical support of LRS for preparation of future system obsolescence.
- Identification of LRS components located internal to the payload tube and external to the host pressure vessel, which are inaccessible during deployment so that design can stress reliability needs for maximized availability and component maintainability when in port.
- Limiting the use of unique components and procedures that affect the ability to complete availabilities on schedule within cost due to parts availability and the use of specialty processes.

The final maintenance requirements and logistics support shall be consistent and compatible with existing VA class submarine practices. This should include the use of Re-entry Control (REC) processes for work in the SUBSAFE boundary. All maintenance should be scheduled in the ships Consolidated Ships Maintenance Plan (CSMP) for accomplishment. Standard Test Procedures should be developed to test the LRS after maintenance and during sea trials.

B. DECISION EVALUATION

1. Background

Decision making under risk and uncertainty is the final step in all System Engineering processes. The goal of decision making was to gather information about many different choices, convert these choices to comparative quantitative and qualitative measures, establish a model that represented the comparisons in a fair and unbiased fashion and demonstrated to the stakeholders that the model identifies the best choice when compared to the stakeholder's value system. [Blanchard & Fabrycky, 2006, pg. 164] Decision-making highlighted the importance of eliciting stakeholder requirements, requirements traceability and re-iterative validation of stakeholder concerns during each process and phase of the Systems Engineering model. Simply put, even the best-engineered systems provide no value to a stakeholder if they do not meet their intended needs.

As would be expected for most engineered systems, the modeling and evaluations conducted with respect to the LRS did not identify one preferred concept alternative. Additionally, based on stakeholder input, life-cycle costs of the system was only one factor in the process. Therefore, to determine which alternative provided the best solution to the war fighter's needs, the team compared the values of each concept alternative.

The value assigned to a system can be considered the "Use" that is expected for the "Investment" into the system. The "Use" of the system can be expressed as the operational capability of a system's functions, performance and quality and can be expressed as a function, or "Use" = *f*(functions, performance, quality). Not all functional capabilities of a system provide equal use to a set of stakeholders or even to one specific stakeholder with respect to other stakeholders. As such, a weighting system was utilized to express those capabilities, which provided greater use vice those which provided less use. This trade-offs of functional capabilities, performance and system quality provided a rationalized approach to the team's final recommendations.

2. Alternative Scoring

To determine the "Use" of each concept alternative, the team examined the results of six (6) areas of comparison accomplished during the Capstone project: Risk, Performance, Interfaces, Reliability, Safety/Usability and Logistics. The examination of concept alternative performance was accomplished via a quantitative approach using the results of modeling and simulation. The examination of the other five factors was done qualitatively using guidance established for each the specific system components. The following rules/guidelines were established to support the analysis:

- Each concept alternative was compared to the other alternatives with respect to the top seven (7) weighted design characteristics (stakeholder requirements) identified in Figure 11. The bottom three (3) weighted design characteristics (System Weight, Payload Space and Data Transfer Parameters) add only 13% (weighting of 1.6 compared to 12.5 total weighting) to the overall concept value. Additionally, the commonality of many concept alternative components with respect to these characteristics provides little separation between rankings of concepts.

- For each area of comparison, at least one (1) alternative was considered best and was assigned a rank of "5" (adds the most "Use"). If the modeling and evaluations resulted in no significant differences between the alternatives, all were assigned a rank of "5".
- The other alternatives not considered the best alternative received rankings of between "1" and "4". No alternative was ranked below "1". In addition, multiple alternatives could be ranked the same if modeling and evaluations resulted in no significant differences between them.
- Comparisons of the alternatives were made against each other alone and not based on outside factors (i.e., reliability with respect to battery charging capacity was made with respect to the proposed system components and did not consider an alternate, theoretical component with anticipated higher reliability).
- The stakeholder value system ranks "Safety" and "Performance" as two of the most desired characteristics for the LRS. Therefore, Safety/Usability and Performance rankings were weighted twice as much as rankings for Risk, Interfaces, Reliability and Logistics.

A table was created for each of the seven (7) design characteristics, comparing each of the concept alternatives in each of the six (6) areas of comparison, resulting in 42 data points for each concept alternative. The "Use" for design characteristic "Recovery Speed" is a summation of the rankings in the six (6) areas of comparison multiplied by the design characteristic weight identified in Figure 11 provides the comparison matrix of the design characteristic "Recovery Speed". Detailed tables for all the comparisons are provided in Appendix F.

The scoring system which potentially ranked one concept 5 times more useful to the stakeholders than another concept identified the possibility of unintended bias. To examine the effects of this bias, the team explored different scoring systems, which, increased or shrank the spread between the rankings of the alternatives. Assuming that the ranks of the concepts in the six areas of comparison were in the correct order, changing the spread did not significantly change the results of the analysis. For instance, using a scoring system of 1, 10, 25, 50, 100 (high penalty for lower ranked alternatives) provided a curve similar to that shown on Figure 48 where Alternative 4 still dominates Alternative 2 for approximately the same cost. Likewise, when the reverse methodology was used and a scoring system of 1, 1.01, 1.025, 1.05, 1.1 (low penalty for lower ranked alternatives) was applied, the results were similar. As such, the team concluded that as long as a scoring system with a reasonable spread was chosen, the final shape of the curve remained unchanged assuming rankings and cost values did not change.

Table 26 – Stakeholder Use Matrix (Recovery Speed)

Recovery Speed	Risk	Performance (x2)	Interfaces	Reliability	Safety/ Usability (x2)	Logistics	Use (Sum of Ranks)
Baseline	1	1	1	1	1	5	27.6
ALT-1	5	4	5	5	5	1	78.2
ALT-2	2	2	2	2	2	4	41.4
ALT-3	5	3	3	4	3	3	62.1
ALT-4	5	5	5	3	5	1	78.2

By summing an alternative's "Use" numbers for all design characteristics, an overall "Use" to stakeholder number was developed for the alternative. These numbers identified in Table 27 and plotted against the Life-Cycle Cost for each alternative in Figure 48. Based on the plot, the Baseline, Alternative 4 (High Tech) and Alternative 1 (Attraction Recovery) dominate Alternatives 2 and 3. Furthermore, assuming Life-Cycle Cost is a consideration but was not the only consideration; Alternative 4 delivered the best Value, defined as Use / Investment to the stakeholders and was recommended for further study. It is noted, as previously discussed, “Use” was a term established to support comparative overall ranking of the alternatives and does not provide a factor of Value for one alternative over another. Hence, Alternative 2 provided nearly the same Value as the best choice (Alternative 4) and would also merit further study to validate costs and trade-offs. Alternatives 1 and 3 provided little additional “Use” for cost and were eliminated from future analysis. The Baseline alternative was comparatively inexpensive but provided little “Use” to meet stakeholder needs and also was eliminated from future analysis.

Table 27 – Stakeholder Use/LCC per Alternative

	Total Use	LCC ($M)
Baseline	140	21.37
ALT-1	297.3	56.25
ALT-2	224.6	41.76
ALT-3	245.8	56.62
ALT-4	285.4	37.36

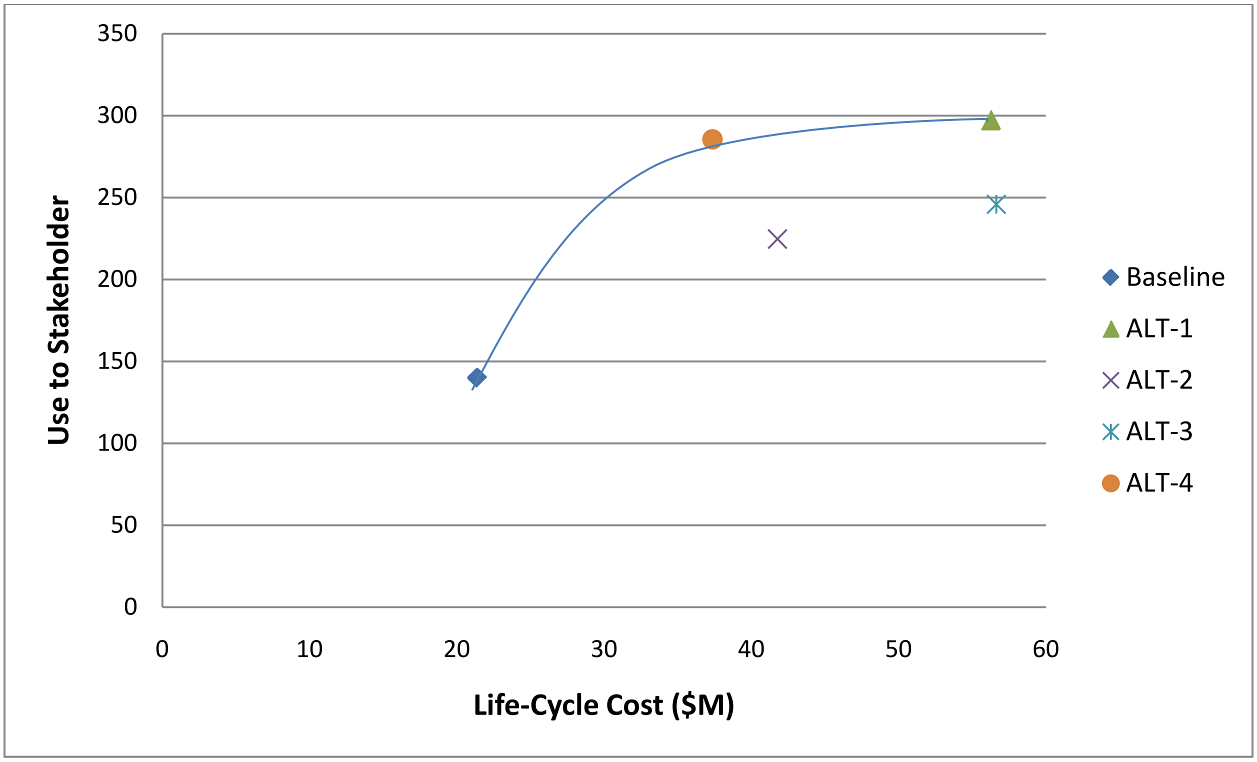


Figure 48 – Concept Alternative Value to Stakeholders

V. SUMMARY, CONCLUSIONS AND LESSONS LEARNED

This Capstone project focused on the considerations and interfaces needed to successfully field and support a system that would launch, recover, replenish, stow and transfer information between current and future Large Vehicle Class UUVs and host submarines, specifically submarines with the VA Class Block III payload tube concept. This system will provide a capability to support persistent–ISR missions identified in the UUV Master Plan of 2004 by providing stealthy information collection capabilities, threat and harbor monitoring, WMD identification and sea floor object reconnaissance.

To accomplish the project objectives, the Capstone team used a three-phase Systems Engineering approach to analyze and develop system requirements, determine system functions, cost and performance guidance and to identify system design needs and constraints. The outcomes and results generated from each phase were validated against a derived value system for the stakeholders and used as the foundation for each successive system engineering phase. Observations and insights of each phase of the project are highlighted below, culminating in a recommended approach to the design and implementation of a system that supports the objectives.

A. PROJECT SUMMARY

System Requirements Analysis

The initial step in the system engineering process was to develop a set of requirements for the LRS. As designs currently exist that integrate UUVs with submarine torpedo tubes and converted SSGN missile tubes, the Capstone team used these concepts as starting points for stakeholder identification and system requirements. During this process, two (2) significant issues were identified; UUV requirements creep and implied problems with current designs.

The UUV Master Plan of 2004 remains as the only documented guidance with respect to persistent-ISR notional capabilities and concepts of operation. In particular, the Master Plan identifies an on-station endurance of 300+ hours (approximately 2 weeks). However, during the course of the Capstone project, three (3) additional documents [Ashton, 2010; Anderson 2011, Taylor, 2011] were issued that discuss on-station endurance goals of between 46 and 120 days. Additionally, Taylor, 2011 discusses a maximum length of 45 feet for a LDUUV (which exceeds the diameter of a VA Class submarine) and highlights the need for payload upgrades, better autonomy and system redundancies. Although all three documents serve to challenge the UUV development community to explore alternate power and control technologies and do not "reset" guidance provided by the 2004 Master Plan, they do highlight the challenges that faced the team with respect to defining the Large Vehicle Class UUV external boundary for the LRS.

Interviews with SMEs identified efforts to integrate a ULRM-like system with VA Class Block III submarines and, potentially, Block IV and Block V submarines. However, responses indicated a variety of concerns and challenges with this approach. For instance, hovering capabilities of SSGN submarines allow a UUV to swim to a deployed cradle while topside recovery by a moving submarine will require both vessels to match speeds and maneuver to avoid the submarine sail. Additionally, current power resources at the forward end of the VA Class submarine may require significant modifications to support replenishment of the UUV power supply. Finally, as shown in Figure 49 and discussed in McDermott, 2011, even the location and design of VA Class submarines with respect to the location and function of the payload tubes remains under review. Although none of these integration issues appear insurmountable, they do represent an approach to UUV/VA Class submarine integration which could increase the cost, schedule and performance risks to the LRS if designers and implementers focus on the wrong requirements and wrong future mission scenarios.

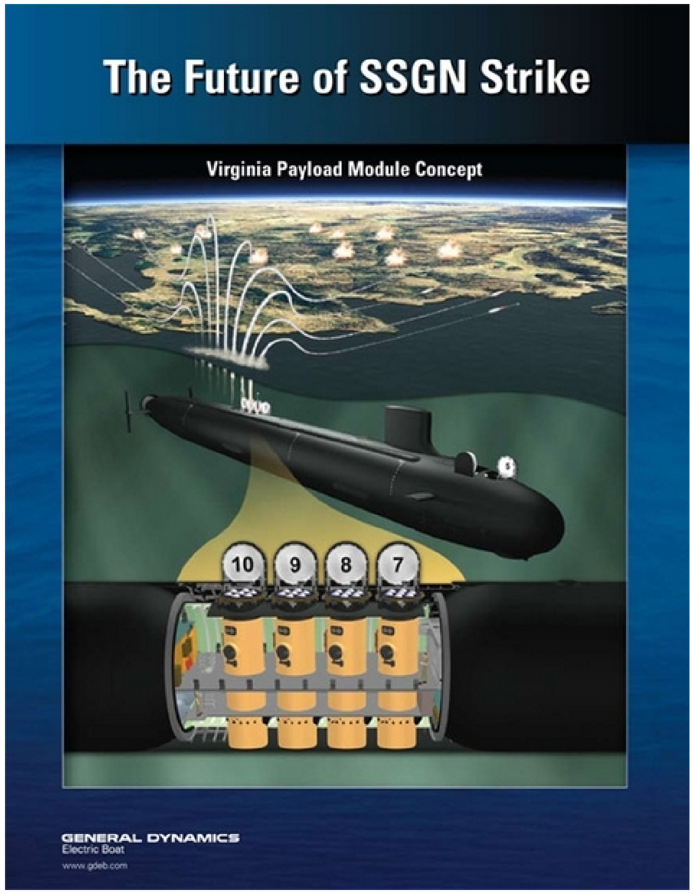


Figure 49 – Proposed Future VA Class Submarine Payload Tube Configuration [McDermott, 2011]

A primary role of the System Engineer is to develop a set of requirements and a preferred approach that provides the best value to multiple stakeholders. To that end, the Capstone team took a long-term approach to establishing system requirements, recognizing that future value which stressed flexibility, safety and life-cycle costs would best serve the stakeholder concerns. Host submarine safety, accommodation of power sources, maximization of launch and recovery performance and system affordability were ranked as the four (4) most critical needs expected for a successful system.

With the requirements for the LRS established, the Capstone team focused on developing the functional architecture. The functional architecture helped identify the resource requirements for the system in terms of equipment and materials, people, support facilities and maintenance/logistics considerations. Using CORE®, by Vitech Corporation, the team accomplished the functional decomposition to map functions to physical component and performers and to map functions to system requirements. The top-level functions of “Launch”, “Recover”, “Maintain” and “Replenish” were established for the system. One internal system performer (Launch and Recovery System Operator) was identified while first-level external performers (Host Submarine Operator, Autonomous UUV) and second-level external performers (Navy Support Agency, UUV Equipment Providers, and Maintenance/Logistics Providers) were assigned the functional responsibilities. With the operational and component hierarchies established, decomposition continued to allocate functions, tasks and requirement to ensure that no necessary actions were missed and no unnecessary actions were included. Functional flow block diagrams were created to verify how information was exchanged between performers and components and operational views (OV-2, OV-5) and system views (SV-4) were generated to pictorially describe the information flows between the aspects of the system.

<u>Functional Analysis</u>

Following development of system requirements and functional architecture, Quality Function Deployment (QFD) models were used to translate the system requirements into distinct system functions and, ultimately, component modules meant to accomplish those functions. Eight (8) component modules were identified and ranked in importance, with the LRS structure and LRS recovery mechanism identified as the two (2) most important. Next, the project team identified technologies, both known and conceptual, which could fulfill system functions for each of the component modules. Finally, these technologies were combined into concept alternatives, ranked according to weightings established during the QFD process and documented as four (4) conceptual alternatives, which could achieve system requirements and provide stakeholder value. To support comparison between the existing concepts and future concepts, a baseline concept was identified to best mirror the functionality of the Universal Launch and Recovery Mechanism (ULRM), a system previously integrated with submarine missile tubes.

The next step was to assess the feasibility of each concept and risks (performance, cost, schedule and programmatic) associated with each concept. As done in technology identification, the Capstone team used experience, lessons learned and peer recommendations to rate concept feasibility and assign risks and potential mitigation plans. A weighted formula combined all risks for a given concept into one value so that concepts could be plotted against each other on one risk matrix. As the four (4) concept alternatives were deemed to perform better than the current, baseline alternative, the baseline alternative was identified as the highest risk concept. None of the other alternatives markedly separated themselves from one another although the Mechanical Recovery Arm alternative offered the lowest risk as the technology is already used in undersea environments. Risk assessment is a qualitative exercise that can instill bias towards certain solutions. However, the Capstone team believed the results of the risk assessment were accurate based on team members experience with acquisition and sustainment of similar submarine systems.

With component concepts and allocated functions for each concept established, lifecycle costs were estimated for each conceptual alternative. Using material cost data from commercial sources and labor/production costs from public shipyards for similar submarine work, the Capstone team established acquisition estimates for a single unit of each alternative. For comparison, the team used a cost data point for a Multiple All-Up Round Canister (MAC), employed in submarine missile tubes. With acquisition costs established, assumptions were made, based on the anticipated reliability of each alternative, to create a maintenance plan over a service life of 20 years. Maintenance costs were determined to be a percentage of acquisition costs for each alternative and were based on comparable maintenance and acquisition costs of submarines in a shipyard environment. To determine a single lifecycle cost in current year dollars, out-year costs were multiplied by a discount factor and all costs were summed.

Cost analysis found that the structural materials were the over-arching cost driver for all alternatives. Structural material costs accounted for between 75% and 90% of the overall acquisition costs for all considered alternatives. As maintenance and sustainment costs leverage off of the acquisition costs, structural material costs contribute a significant amount of the overall lifecycle cost to each concept alternative. As such, the Baseline Alternative, which uses a relatively cheap high strength steel structural material, had a lifecycle cost of $16M less than the nearest alternative, even with a more extensive maintenance and sparing plan. However, the use of steel in a seawater environment adds additional risks with respect to corrosion and component failure as well as adds weight and reduces payload volume to provide the necessary structural strength. The titanium alternatives, while considered the “soundest” material with respect to structural strength per volume of material, were also the most costly alternatives. Sensitivity analysis and examination of future titanium pricing trends vice carbon fiber composite and high strength steel pricing trends found significant pricing risks as growing competition is expected to deplete titanium sponge resources. Carbon fiber composite alternatives provided a middle-of-the-road cost approach to the metallic alternatives. Estimates for carbon fiber capital equipment such as molds and manufacturing processes were difficult to reflect and may skew current estimates somewhat higher than the team estimates of $4M for initial capital costs. However, as the raw materials for carbon fiber materials are inexpensive and plentiful, future costs may trend downward as manufacturing processes improve and competition forces pricing consideration. As such, the team considers life-cycle pricing estimates valid.

Additionally, since raw material cost per pound of carbon fiber and titanium are about equal and since titanium weights twice as much as carbon fiber, a titanium structure was still estimated to cost twice as much to actually fabricate. The Capstone team agreed that it would be possible to make a titanium structure which weighted only ½ as much as a comparable carbon fiber structure, this detailed design analysis was beyond the scope of the project. Furthermore, making any structures with hollow tubes would violate principles that restrict implodable volumes in submarine external compartments and would make it much more difficult to remove half the weight from a titanium structure.

Concurrent with cost analysis, modeling and simulation was accomplished to analyze the performance effects on the LRS concepts under a variety of input conditions. Using the system's top-level functions of "Launch", "Recover", "Maintain" and "Replenish" as starting points, the Capstone team generated a mission model in ExtendSIM® designed to focus on testable key performance parameters such as launch and recovery success (as a function of overall system reliability), launch and recovery speed and system replenishment time.

Modeling parameters for each concept alternative and were derived, to the maximum extent practical, by evaluating the component composition of each alternative. The team made reliability and speed-related assumptions using known or derived values for USS LOS ANGELES CLASS (SSN 688) submarine missile launch data and commercial specification data for similar products. Additionally, to add a sense of realism to the mission model, the team used weather and sea traffic assumptions for a potential mission area (Strait of Hormuz).

Modeling and simulation results showed a mixed solution. For instance, Alternative 1 – Attraction Recovery, performed best with respect to overall launch and recovery success (reliability) whereas Alternative 4 – Performance Option, performed best with respect to overall cycle time. Under the Operational Situation (OPSIT) parameters, Alternatives 1 and 4 dominated Alternatives 2, 3 and the Baseline in all measures. However, down-select between Alternatives 1 and 4 could not be based simply on performance alone.

The performance models were adjusted to examine component sensitivity and the overall validity of the model. By selecting reliability values of between 5% and 15% different from the tolerance values established in the performance input assumptions, model results still showed a preference for Alternatives 1 and 4. As such, barring significant errors made in the team's selection of the input assumptions, the model would be expected to consistently identify Alternatives 1 and 4 as the superior choices. Also of interest, the Launch and Recovery system overall reliability was set at 100% so that only external factors (weather, UUV, host submarine) would affect launch and recovery success. For all alternatives except the Baseline, mission success was about 90%, which corresponds fairly well with the team's anticipated A_o and mission success rate derived from similar submarine functions.

Detail Design Considerations

Design Considerations qualitatively assessed the risks associated with proceeding into design and fabrication of the conceptual alternatives. As the over-arching Feasibility Analysis and Concept Risk Analysis conducted during the Functional Analysis Phase, Design Considerations assessed the characteristics the LRS should possess to minimize negative cost, schedule, performance or programmatic results. However, Design Considerations focused on specific areas, with considerable concentration on interfaces, and recommended not only material concerns to mitigate risks but also procedural and planning steps necessary to help remove risks from design, production, testing and maintenance/support of the LRS.

The analysis looked at interfaces between internal and external systems. While risks between internal component interfaces would be managed through sound architecture, the team found considerable issues are likely with the internal/external interfaces. Unlike on SSGN submarines, the Virginia Payload Tubes (VPT) on VA Class Block III submarine is located external to the pressure hull. Physically interfacing the system components inside the submarine with those outside the submarine would require hull penetrator back-fits to both the submarine and to the VPT. Hull penetrators must not only be capable of transmitting data, they are also required for power replenishment. Additionally, the shape and size of the Large Vehicle Class UUV and desired number of UUVs stowed in a system will alter considerations for LRS clamping devices and stowage devices. The risks of significant rework to the LRS, host submarine and UUV could all be significantly mitigated by early and frequent communications between all stakeholders.

System Safety and Usability Analysis and Logistics Analysis examined potential materials/designs for concept alternatives and recommended considerations to lessen the risks associated with fielding a successful system. While material choices and design were obvious considerations to eliminate hazards and maintenance issues, equally important were human factors and policy constraints. With technology advances, needs for skilled craftsmen must be identified early to support maintenance needs. Also, the unique submarine operating environment cannot support a system that releases significant amounts of explosive gasses or requires submerged operations with obstructed hull closure devices. Again, early and frequent lines of communication would be required to mitigate design issues.

Reliability Analysis used block diagrams to represent different system configurations, seeking to maximize a reliability growth strategy. While a simple model that places the four top-level system functions in series results in the lowest cost option, it also creates the lowest system reliability output as it is susceptible to a single-switch failure. Noting that electronics and software provide a significant amount of functionality to the system's "Replenish" and "Maintain" functions, the team proposed adding a level of redundancy to these functions. These additions would come at an overall low cost, will focus on system interface areas where risk is high and will not add significant weight nor significantly reduce the payload volume. Furthermore, as mission and data functionality/requirements evolve, electronic and software component alterations provide the best mechanisms to invoke these changes for minimal cost. As a result, this alteration would result in an overall system reliability of ~79% vice ~66% for system in series (assuming 90% reliability for each component package).

The Software Development Plan, Test, and Evaluation Strategy provided recommended guidelines to minimize the risks at final operational testing and provided areas for technical assessment of the system during design and demonstration. Both processes champion open sourcing of materials to the maximum extent practical vice design-from-scratch. Both processes also recognize the need for significant government oversight of contractors during development and leveraging of unit testing, modeling and laboratory demonstration testing as practical. As final operational testing will employ a VA Class Block III submarine asset, integration of all systems and combined demonstration / operational testing in a test tank will support the necessary troubleshooting prior to the final fielded event.

B. CONCLUSIONS

Of the concept alternatives explored, Alternative 4 (Figure 39) provides the best value to the stakeholders for the investment. Alternative 4 demonstrated superior modeling and simulation performance times with an acceptable rate of success. Acquisition costs were mid-range while sustainment costs were comparatively low due to high reliability and maintainability of the structure, redundant features and lack of frictional wear issues.

Specific technologies for concept component packages and the pros and cons for the technologies were based on Capstone team experience, discussions with peer-groups and available literature. Future technologies might result in alternative groupings that provide superior value to the stakeholder at equal or less investment; however, the Capstone team concludes that there are several characteristics were keys to any successful system. As shown in Table 27, Alternatives 2 and 4 offered similar use to the stakeholders and at a similar investment. Characteristics found in these alternatives, detailed below, offer a blueprint for a successful LRS that could meet stakeholder requirements and changes into the future:

- Structural components are the most significant cost driver, both in acquisition and maintenance. While a carbon fiber composite structure (specified for Alternatives 2 and 4) offer weight reduction, noise reduction and corrosion resistance at a stable future price, issues with robustness, especially in torsion, add risk to the design.

Additionally, design changes may require re-molding of large parts vice small, in-place modifications. Ideal solutions should consider the significant advantages composites offer and explore ways of correcting the shortfalls. Potential solutions might involve molding metallic components into the composites at manufacture to provide a surface to bear loads and a foundation for simple future modifications.

- Successful launch and recovery mechanisms must be adaptive and must minimize submarine dwell time. UUV shapes, sizes and material considerations make systems that rely on clamps, magnets and sleds slow and restrictive. Instead, until UUV technology produces a vehicle that matches speed with the submarine and automatically maneuvers to its capture device, system should focus on remote capture while in motion. Devices that produce a low-pressure pocket that draws the UUV to the submarine or that remotely capture and pull the UUV to the submarine offer the most promise to adapt and reduce dwell time.
- Simple designs not only decrease risk, they also improve reliability. For the LRS, simple did not mean devoid of technological advances; instead, it meant systems that multi-task and systems that still function in the event of minor failures. A combination launch and recovery mechanism with similar mechanical components and built-in redundancy for the controls and functions of the components should be considered as a design solution. Exploration of mechanisms, which function at or near full capacity in sub-optimal situations, such as induction power replenishment, can reduce the reliance on other mechanisms to always operate without error.

C. LESSONS LEARNED

The successful implementation of autonomous, unmanned systems into the underwater battle space will continue to challenge US Navy leadership, technical experts and the acquisition community for decades into the future. As unmanned air vehicles has allowed the US military to conduct around-the-clock air surveillance and targeting of adversaries with little risk to military personnel and manned assets, the UUV community will constantly be challenged to perform equally well in deep sea and littoral environments. During the progression of this Capstone project, several lessons learned were identified which should be considered for UUV/submarine integration projects and studies.

Requirements Stability - Stakeholders should consider re-visiting the mission and operational parameters established for persistent –ISR operations in the 2004 UUV Master Plan. Particular emphasis should be focused on endurance requirements for perceived missions and whether it is feasible, in the near term, to field UUVs launched from submarines to meet those requirements. If not practical, stakeholders might consider near-term mission guidelines that support current capabilities, such as an incrementally fielded approach. If endurance requirements established in Ashton, 2010, Anderson 2011 and Taylor, 2011 are mandatory, fielding of multiple Large Vehicle Class UUVs in a rotational pattern might be considered an option.

Submarine/UUV System Certification Issues - UUVs and their launch/recovery mechanisms can pose a widespread and detrimental effect to the host submarine and submarine personnel. As the UUV and launch/recovery equipment are stowed within boundaries of contained submarine structure, toxic, flammable and explosive materials can result in catastrophic effects where similar materials used in unmanned air or ground vehicles may pose little to no issues. Additionally, equipment weight, launch and separation reliability, shock resistance and flood control measures affect the host submarine in ways not shared by other unmanned vehicle host platforms.

While governing ASTM guides provide guidelines for the capabilities of UUVs, they do not specifically address constraints related to submarine launch and recovery platforms. US Navy leadership needs to recognize that submarine launched and recovered UUVs are a family of systems with constraints unique to land-based systems. Integration issues, particularly those related to submarine safety issues, require early and on-going teaming between the stakeholders of the two primary external boundary systems.

Modularity/Flexibility - UUV manufacturers continue to explore technologies meant to break through constraints that limit current capabilities. Many of these technologies, such as fuel cells and increasingly autonomous controls may not be mature enough to support a fielded unit for 5 or more years into the future.   However, when successfully implemented, they stand to dramatically change the way a UUV would be integrated with a submarine. For instance, UUV diameter and length would be significantly larger to accommodate large energy sources. In addition, re-fueling may come in a form of a gas or liquid vice electricity, or, in some cases, may not be required at all. To support these incremental changes to UUV size, make-up and capabilities, future studies should focus on the flexibility and/or modularity of a launch and recovery system. Trade-off studies might examine components, which could effectively be modified vice completely re-designed to accommodate change. Close relationships with UUV designers and manufacturers would be required to support plausible visions into the future while limiting sacrifices to performance and acquisition costs.

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APPENDIX A – PROJECT MANAGEMENT PLAN ROLES AND RESPONSIBILITIES

This appendix provides specific details with respect to the team's roles, responsibilities, actions and deliverables related to the work on this capstone project.

Project Team Organization

The UUV-ISR project team was organized in accordance with Figure 1 below:

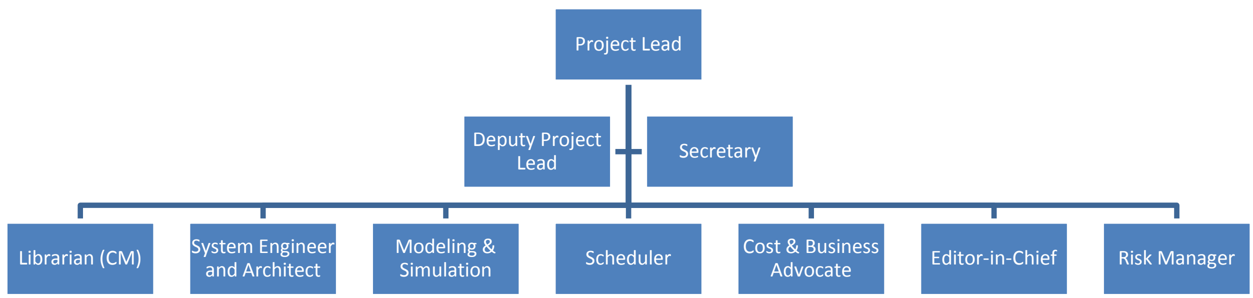


Figure 1 – UUV-ISR Project Team Organization

The UUV ISR project team consists of seven engineers, all employed by Naval Sea Systems Command (NAVSEA) and co-located at the Washington Navy Yard. Combined, the team possesses 80 years of experience on submarine design, operation, maintenance and sustainment. Engineering experience of team members is general and broad in nature. No member of the team is a Subject Matter Expert on a specific area or technology that relates to this analysis.

Due to co-location of team members and broad vice specialized area of expertise, the use of Integrated Project Teams will not be employed for this project. Instead, all team members will participate, in general, on all aspects, with individual team members assigned leads for the identified roles and responsibilities. Additionally, due to small team size, most members will be dual-hatted and serve more than one team role. Table 1 is a listing of each team member's primary roles and responsibilities. Roles and responsibilities are subject to change as the project progresses and needs arise.

Table 1 - UUV Team Members Roles & Responsibilities

Name	Roles & Responsibilities	Locat ion
Calvert, Bill	Project Lead, Assistant to Editor-in-Chief, Secretary	NAVSEA
Malecki, Sarah	Deputy Project Lead, Editor-in-Chief, Secretary	NAVSEA
Goodman, Gail	Scheduler, System Engineer and Architect, Secretary	NAVSEA
Lojek, Joe	Cost and Business Advocate, Secretary	NAVSEA
Powell, Brian	Modeling & Simulation, Secretary	NAVSEA
Heidt, Brian	Librarian (Configuration Manager), Assistant to Modeling & Simulation, Secretary	NAVSEA
Cohn, Rachel	Risk Manager, Secretary	NAVSEA

Project Lead

The project lead is responsible of overall management and execution of the project in accordance with the project management plan. The lead will develop the agenda for team meetings, conduct team meetings, coordinate action items and assign due dates. The lead will ensure the balance of resources was adequately distributed to support the technical abilities of the team members and support the scheduled delivery of technical products. The lead will serve as the primary Point-of-Contact (POC) with the project advisors.

Deputy Project Lead

The deputy project lead will assume the duties of the project lead in their absence and will serve as a secondary POC with project advisors.

Secretary

The secretary is a rotating position that will be assigned at each team meeting. The secretary will be responsible for the creation and distribution of meeting minutes for the team, to include action items and due dates assigned as a result of team meeting discussions. The secretary will maintain the project engineering journal for the team, submitted to the secretary by all team members, as practical, on a weekly basis.

Librarian

The librarian is the Configuration Manager (CM) for the project team and will be responsible for the communications plan for the team. The librarian will maintain an auditable trail of documentation and will enforce version control to project deliverables per the details of the communications plan. The librarian will provide means and traceability for performance and effectiveness of alternate system designs back to stakeholder requirements.

System Engineer and Architect

The system engineer/architect is responsible for defining and implementing the systems engineering approach to the development of the project. The system engineer/architect will serve as project team lead for stakeholder requirements definition, requirements analysis and architectural design for the proposed system. The system engineer/architect will lead establishment of system Measurements of Effectiveness (MOE) and Measurements of Performance (MOP) necessary to evaluate alternate design options. The system engineer/architect will support functional and process decomposition of operational activities and will develop input requirements, functions, components and relationships necessary to develop the system architecture.

Modeling & Simulation

The modeling and simulation (M&S) lead is responsible for development and implementation of functional performance models and operational performance models as means to compare the performance and effectiveness of various system alternatives. The M&S lead will provide verification and validation of models to stakeholder requirements and will provide analysis of simulation results to support trade space analysis.

Scheduler

The scheduler will develop the project schedule and track progress versus planned due dates. The scheduler will maintain and active, real-time model of the project schedule, available to all team members and will establish critical path functions requiring the attention of all team members.

Cost and Business Advocate

The cost and business advocate will develop models to analyze the Life-Cycle Costs (LCC) that assess the affordability of various system alternatives. The advocate will utilize Cost as an Independent Variable (CAIV) to support cost-benefit analysis for potential system alternatives. The advocate will have the lead responsibility to generate estimated life-cycle costs of alternatives using historical data, standard parameters or like comparisons with similar components, processes and procedures.

Editor-in-Chief

The editor-in-chief is responsible for development and delivery of technical documents for the project team. The editor-in-chief's responsibilities include formatting, spelling/grammar, and establishing the cohesiveness of the technical documents from the submittals of the various team members. The editor-in-chief will utilize the text recommended by project advisors for development of the team's technical documents.

Risk Manager

The risk manager will assess potential areas of technical, schedule and cost risks associated with system requirements and project implementation. The risk manager will develop assessment of risks, recommend actions associated with avoidance, assumption, transfer or mitigation of risks and manage actions related to reduction of risks. Risk Management and Analysis will be conducted in accordance with the Risk Management Guide for Department of Defense (DoD) Acquisition and NAVSEA Instruction (NAVSEAINST) 5000.8, Naval Systems Command (SYSCOM) Risk Management Policy of 21 July 2008.

Project Advisors

The UVV-ISR project team advisors are Dr. Jeffery Beach and Professor Mike Green. Both are Naval Post-Graduate School (NPS) faculty members in the Department of Systems Engineering. In addition, Professor Green is an experienced submariner.

Project Team Configuration Management Plan

The UUV-ISR Team Configuration Management Plan (CMP) provides guidelines for the UUV-ISR project. The CMP covers five aspects of the UUV-ISR project: Electronic Files, Communications, Meetings, Classroom Data and Information Distribution.

Electronic Files

A. Document Repository:

The UUV project will use Google Docs as an online document repository for files and information relevant to the project. Each team member will have access to the Google Docs site and obey the configuration management guidelines outlined in this plan. A group account has been set up to allow individual group members or advisors to access the Google Docs site.

Username: NPSTeamA

Password: NPScapstone

Once a file has been posted to the Google Docs site, the team member responsible for posting the file, will send out an email notification (via Google Docs) to the Team and if necessary Team Advisors, with any pertinent messages on the file.

B. File Naming Convention:

All electronic files supporting the UUV project completion effort are grouped into 10 categories (represented as folders on the Google Docs site): **Archive, Class Chat box, CORE, Engineering Notebook, ExtendSim, Final Report, Interim Assignments, IPR#2, Meeting Minutes, and References**. All files are given the following naming convention:

"filename.yy.mm.dd.rev" - example, the first revision of the Project Management Plan written on October 11, 2010 would be titled: "UUV Project Management Plan.11.10.10.0". Subsequent revisions on the same day would be titled ""UUV Project Management Plan.11.10.10.**1**" and "UUV Project Management Plan.11.10.10.**2**" etc.

If a new revision is posted on a subsequent date, the filename description does not change, only the date and revision change.

C. Working Copies:

To prevent two team-members working off of the same draft simultaneously, the latest working entry will be titled "fileanme.yy.mm.dd.rev.working". The ".working" indicates that active changes are being made to the latest revision, and other team members should not attempt to make changes. The ".working" file can be a dummy document only used as a posted placeholder to indicate that a team-member is modifying the latest document. This posting will be made as soon as modification starts. The ".working" file will be deleted once the new revision has been completed and posted.

D. E-Mail Policies:

To prevent clogging and overloading of email inboxes, electronic project files will not be emailed to other team members. All electronic files will be posted to their appropriate folder on the designated team site.

Communications

Team communications will take place via four (4) mediums: E-mail, telephone, Elluminate sessions, and in-person meetings.

E-Mail: To maintain configuration control of group discussions, e-mail shall not be used for group discussions or comments. Group e-mail will **only** be used for file posting notification and meeting announcements. One group representative will engage professors/advisors via email and post relevant responses on Google Docs. Other group members will not be included on the "cc" or "bcc" fields of these emails.

Telephone: If the team, or select individuals, participates in a teleconference or telephone call, the minutes or results of the conversation shall be posted to the "meeting minutes" folder on Google Docs.

Elluminate: When the group engages in meetings via Elluminate, the session shall be recorded and posted (if possible) to the "meeting minutes" folder on Google Docs. If the file was not recorded, or if posting is not possible, minutes shall be recorded and posted to the meeting minute's folder.

In-Person Meetings: Face to face meetings will be scheduled via email in the form of a meeting request. Minutes will be recorded and posted to the "meeting minutes" folder.

Meetings

Meetings will be scheduled by the team scheduler and attended by as many team members as possible.

Regular team meetings are scheduled for Tuesdays, 1530 to 1700, EST. Elluminate meetings with Project Advisors are scheduled for Wednesdays, 1800 to 1900, EST. Other meetings as necessary will be scheduled by the designated team scheduler.

Minutes will be recorded at every team meeting. Minutes should include team members in attendance, guests, time and date of meeting and any action items from the meeting. Meeting minutes will be posted to the “meeting minutes” no more than 24 hours after a team meeting, when practical.

If any action items are assigned at team meetings, the action shall be written down in full, as well as the team member the action is assigned to and the date the action is to be completed. Action items will be included in the meeting minutes.

Meetings will take place in one of three venues, In-person, Telephone Conference or via Elluminate session.

Class Data

Class data captures the Monday Elluminate session, if held.

A recording of each Elluminate session will be made and if possible posted to the “meeting minutes” folder on Google Docs. If this is not possible, then the default session location on Elluminate will suffice.

A team member will be responsible for copying the entire class chat window from every Monday Elluminate session and posted as a separate file to the “class chat box” folder on Google Docs.

Information Distribution

All data will be taken from and released as Distribution A (available for public release). This project will not use any data from distribution sources other than Distribution A unless prior consent is gained by the appropriate classification agency.

Project Deliverables

Table 2 outlines the deliverables and milestones associated with the proposed project. Prior to satisfactorily completing a milestone, all deliverables must be satisfied per review by the UUV-ISR team and the system's active stakeholders.

Table 2 - Deliverables & Milestones

Deliverable and Milestone	Approx. Completion Date
Final Project Management Plan Submitted	28 Oct 2010
NPS SE Chair Approves Project Management Plan	19 Nov 2010
In-Process Project Advisor Review No. 1	6 Dec 2010
In-Process Project Advisor Review No. 2	14 Mar 2011
Final Capstone Report Draft Submitted	11 May 2011
Final Reviewed and Concurred Report Submitted	1 June 2011
Final Capstone Briefing Accomplished	6 June 2011

Project Risk Management Plan

Purpose

The purpose of the Risk Management Plan (RMP) is to outline the strategy that will be followed to manage risk within the team's program. Risk is a measure of future uncertainties in achieving program performance goals and objectives within defined cost, schedule, and performance constraints.

The RMP will not identify or address specific risks, but rather will serve as general guidance and instruction. Individual risks will be identified and managed in a working document titled Risk Analysis Document.

Risk Management Plan Process Model

The Risk Management Process Model, as described in the Risk Management Guide for DoD Acquisition, consists of five activities: risk identification, risk analysis, risk mitigation planning, risk mitigation plan implementation, and risk tracking, as illustrated in Figure 2, which are performed on a continuous basis, throughout a system's life cycle.

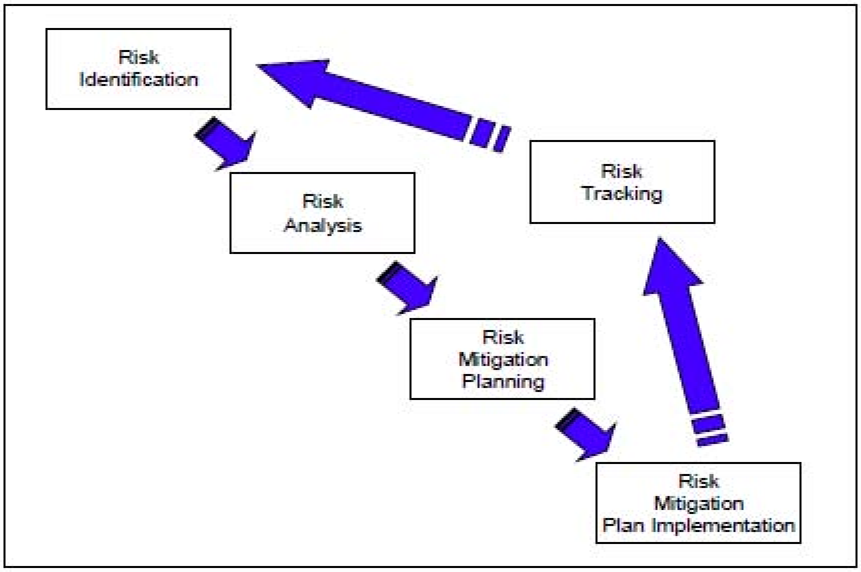


Figure 2 – DoD Risk Management Process

Risk Management Activities

Risk Identification: Risk identification is the activity during which each element of our program will be examined, in order to identify risk root causes, so that appropriate action can be taken to manage them. All team members will participate in identifying risk root causes on an ongoing basis. Risks will be identified by:

- Looking at current and proposed staffing, design, resources, etc…
- Reviewing potential shortfalls against expectations
- Monitoring results of testing and simulation
- Analyzing negative trends

Figure 3 is a risk breakdown structure, in which risk is decomposed into categories. This is a helpful tool in identifying root causes.

Risk Analysis: During the risk analysis activity, we will determine how significant a risk is by determining the likelihood of the root cause occurrence, and identifying possible consequences if the root cause were to occur. This information will be used to plot each risk in a Risk Reporting Matrix, Figure 4.

The level of likelihood of each root cause is established using the table shown in Figure 5, and the level of consequence of each root cause is established using the table show in Figure 6. When categorizing the level of consequence for a root cause, we will first identify if the primary consideration is performance, schedule, or cost. Thus, if the primary consequence of a root cause is a significant degradation in technical performance, but the cost and schedule are not impacted considerably, then the level of consequence for this root cause shall be a four (4). Low levels of risk are reported in green, moderate risks are in yellow, and high risks are in red on the Risk Reporting Matrix.

Risk Mitigation Planning: During the risk mitigation planning phase, the team shall develop an approach to address each risk. Options for mitigating risk include:

- Avoiding risk by eliminating the root cause and/or consequence
- Controlling the cause or consequence
- Transferring the risk
- Assuming the level of risk and continuing on the current program plan.

Note that assuming the level of risk will not be an acceptable option for moderate and high risks.

The following topics will be addressed and documented for each identified risk in the Risk Analysis Document:

- Descriptive risk title
- Description of risk, to include a summary of impacts, likelihood of occurrence, consequence, and whether the risk is within the control of the program
- Root causes leading to the risk
- Mitigation options
- Events and activities intended to reduce risk, and subsequent level of risk if successful
- Recommendation for mitigation
- Resource needs

Risk Management Plan Implementation: During the risk mitigation plan implementation phase, the chosen risk mitigation strategy identified in the previous phase shall be executed. Risk reporting requirements for on-going monitoring shall also be identified.

Risk Tracking: The risk tracking phase shall be implemented to ensure successful risk mitigation. This will be done by monitoring risk mitigation plans, reviewing regular status updated, and reviewing program metrics as applicable.

Risk tracking shall be conducted on a periodic basis throughout the length of the program. Known risks shall be reevaluated to account for the updated information, and the program shall be examined for new root causes.

Responsible Organizations

All team members will play an active role in risk management. Primary responsibility for risk management shall belong to the Risk Manager. The Risk Manager will be in charge of creating and updating the Risk Analysis Document. All team members will contribute to the risk identification phase. The Risk Manager will be the lead for risk analysis, risk identification, and risk mitigation planning. Team members may be asked for input during these activities, and will review the Risk Analysis Document for accuracy. Team members will implement the risk mitigation strategies identified. The Risk Manager shall track risk based on input from team members.

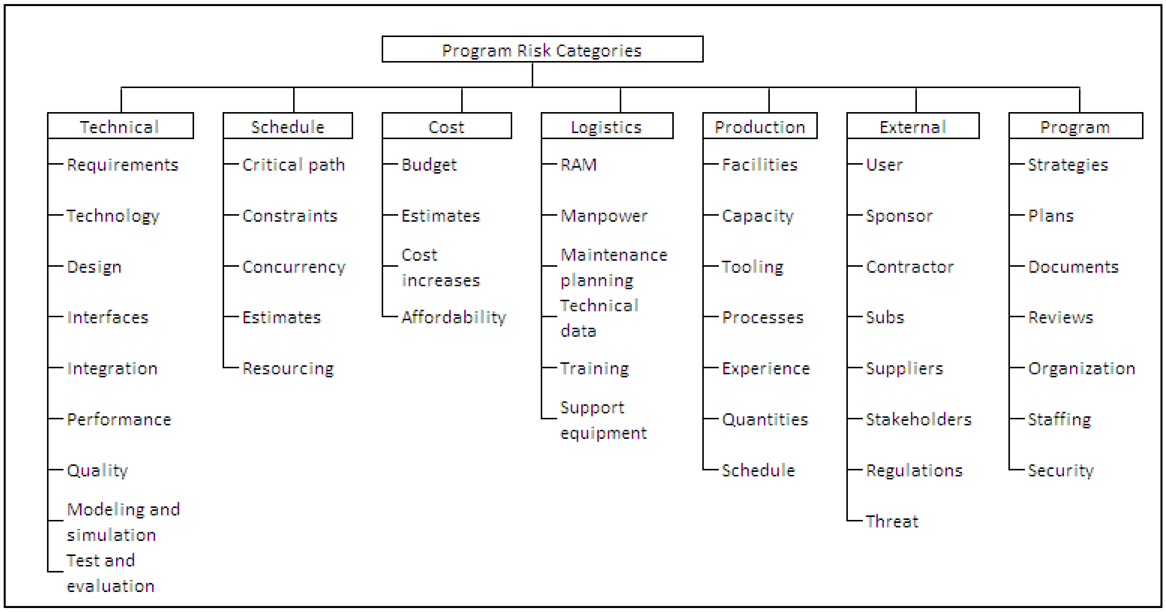


Figure 3 - Risk Breakdown Structure

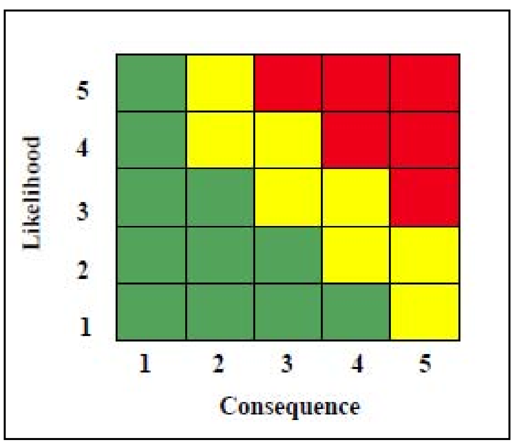


Figure 4 - Risk Reporting Matrix

Likelihood

Level	Likelihood	Probability of Occurrence
1	Not Likely	~10%
2	Low Likelihood	~30%
3	Likely	~50%
4	Highly Likely	~70%
5	Near Certainty	~90%

Figure 5 - Levels of Likelihood Criteria

Consequence

Level	Technical Performance	Schedule	Cost
1	Minimal or no consequence to technical performance	Minimal or no impact	Minimal or no impact
2	Minor reduction in technical performance or supportability, can be tolerated with little or no impact on program	Able to meet key dates. **Slip < * month(s)**	Budget increase or unit production cost increases. **< ** (1% of Budget)**
3	Moderate reduction in technical performance or supportability with limited impact on program objectives	Minor schedule slip. Able to meet key milestones with no schedule float. **Slip < * month(s)** **Sub-system slip > * month(s) plus available float.**	Budget increase or unit production cost increase **< ** (5% of Budget)**
4	Significant degradation in technical performance or major shortfall in supportability; may jeopardize program success	Program critical path affected. **Slip < * months**	Budget increase or unit production cost increase **< ** (10% of Budget)**
5	Severe degradation in technical performance; Cannot meet KPP or key technical/supportability threshold; will jeopardize program success	Cannot meet key program milestones. **Slip > * months**	Exceeds APB threshold **> ** (10% of Budget)**

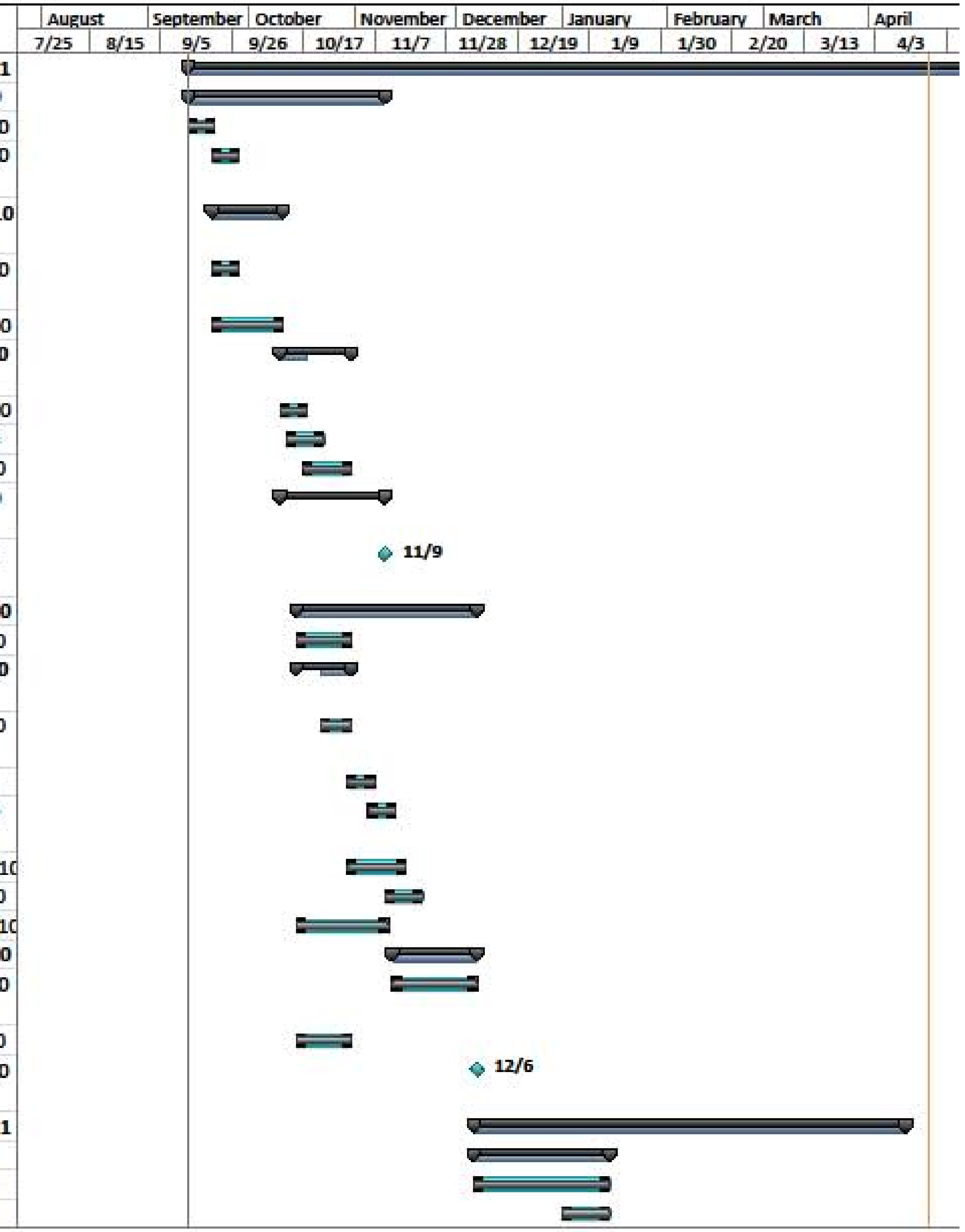
Figure 6 - Levels of Consequence Criteria

The Work Breakdown Structure (WBS) presented here is the most current revision at the time of submission of this document. The WBS will be handled as a separate document to be updated throughout the project.

1. Unmanned Undersea Vehicle/Submarine Integration Project
    - 1.1 Initiate Project
        - 1.1.1 Establish Team Roles and Responsibilities
        - 1.1.2 Establish Team Communication/Configuration Management Approach
        - 1.1.3 Identify Stakeholders/Subject Matter Experts (SME) in Sphere of Influence
            - 1.1.3.1 Interview Stakeholders/SME and Document Meeting Minutes
            - 1.1.3.2 Document Key Stakeholders and Proposed Needs
        - 1.1.4 Establish Capability Need, Scope and Objective of Project
            - 1.1.4.1 Document Need/Scope/Objective to Advisors
        - 1.1.5 Establish System Engineering Approach
        - 1.1.6 Establish Risk Management Approach
        - 1.1.7 Develop Project Management Plan (PMP) to Codify Project Approaches
            - 1.1.7.1 Obtain Department Chair Approval of PMP **(Deliverable)**
    - 1.2 Conduct Requirements Analysis & Verification Phase
        - 1.2.1 Compile Capability Gaps/ Needs from SME Interviews
        - 1.2.2 Compile Capability Gaps/Needs from Literature Research
            - 1.2.2.1 Establish Proposed Project Requirements and KPPs/KSAs
        - 1.2.3 Conduct Requirements Trade-off Assessments
        - 1.2.4 Verify Requirements to SME and Literature Research Gaps/Needs
        - 1.2.5 Document Ranked Project Requirements and KPP/KSAs
        - 1.2.6 Define Project Risks and Feasibility
        - 1.2.7 Define Mission Capabilities and Operational Activities
        - 1.2.8 Define Proposed Scenarios for System
            - 1.2.8.1 Document Proposed Measures of Mission Success (MOE and MOP)
        - 1.2.9 Establish Preliminary Final Report Outline
        - 1.2.10 Conduct Interim Progress Brief #1 of 1st QTR Work **(Deliverable)**
    - 1.3 Conduct Functional Analysis & Verification Phase
        - 1.3.1 Define Hierarchy and Decompose System Architecture
            - 1.3.1.1 Document System Architecture into CORE
            - 1.3.1.2 Identify System Interfaces/Assess Risks
        - 1.3.2 Develop Functional and Behavioral Models of System
            - 1.3.2.1 Conduct Trade-offs of MOE & MOP
                - 1.3.2.1.1 Document Final MOE & MOP and Metric for Measurements
        - 1.3.3 Verify MOE & MOP Support Stakeholder Needs
        - 1.3.4 Using Top Level Architecture (Functions), Conduct QFDs
            - 1.3.4.1 Document Alternatives (Morphological Matrix)

1.3.5 Conduct Scoring to Identify Top Alternatives
1.3.5.1 Conduct Design Trade-off Analysis and Assessments
1.3.5.2 Establish Value and Worth Scoring for Stakeholders
1.3.5.3 Define Concept Alternative Risks and Feasibility
1.3.5.4 Establish Life-Cycle Cost Estimates for Top Alternatives
1.3.5.5 Model and Simulate OPSITs for Alternatives
1.3.5.5.1 Determine MOE & MOP Measurements for Alternatives
1.3.5.5.2 Perform Modeling of Alternative Functions
1.3.5.5.3 Perform LRS Sensitivity Analysis
1.3.6 Conduct Team System Functional Review
1.3.7 Conduct Interim Progress Brief #2 of 2nd QTR Work **(Deliverable)**
1.4 Conduct Design Synthesis & Verification
1.4.1 Conduct Cost-Benefit Analysis
1.4.1.1 Determine CAIV
1.4.2 Conduct Interface And Design Analysis
1.4.2.1 Develop Test Strategy
1.4.2.2 Develop Hardware/Software Integration Plan
1.4.2.3 Assess Safety and Usability
1.4.2.4 Assess Logistics Support
1.4.3 Conduct Reliability Analysis
1.4.4 Propose Final Design Recommendation
1.4.5 Validate Final Design Recommendation with Stakeholder Requirements
1.4.6 Determine Future Exploration Avenues
1.5 Project Conclusion
1.5.1 Complete Draft Final Report
1.5.1.1 Submit to SE Department Advisors and Secretary for Review **(Deliverable)**
1.5.2 Adjudicate Comments and Submit Final Project Report **(Deliverable)**
1.5.3 Develop Project Presentation
1.5.3.1 Deliver Project Presentation for Faculty and Stakeholders **(Deliverable)**

ID	Task Mode	Task Name	Duration	Start	Finish
1		Unmanned Undersea Vehicle/Submarine Integration Project	200 days	Mon 9/13/10	Wed 6/15/11
2		Initiate Project	43 days	Mon 9/13/10	Tue 11/9/10
3		Establish Team Roles and Responsibilities	6 days	Mon 9/13/10	Mon 9/20/10
4		Establish Team Communication/Configuration Management Approach	6 days	Mon 9/20/10	Mon 9/27/10
5		Identify Stakeholders/Subject Matter Experts (SME) in Sphere of Influence	16 days	Mon 9/20/10	Sun 10/10/10
6		Interview Stakeholders/SME and Document Meeting Minutes	6 days	Mon 9/20/10	Mon 9/27/10
7		Document Key Stakeholders and Proposed Needs	16 days	Mon 9/20/10	Sun 10/10/10
8		Establish Capability Need, Scope and Objective of Project	17 days	Sun 10/10/10	Sat 10/30/10
9		Document Need/Scope/Objective to Advisors	7 days	Sun 10/10/10	Sun 10/17/10
10		Establish System Engineering Approach	9 days	Tue 10/12/10	Fri 10/22/10
11		Establish Risk Management Approach	12 days	Sun 10/17/10	Sat 10/30/10
12		Develop Project Management Plan (PMP) to Codify Project Approaches	23 days	Sun 10/10/10	Tue 11/9/10
13		Obtain Department Chair Approval of PMP (Deliverable)	1 day	Tue 11/9/10	Tue 11/9/10
14		Conduct Requirements Analysis & Verification Phase	37 days	Fri 10/15/10	Mon 12/6/10
15		Compile Capability Gaps/ Needs from SME Interviews	12 days	Fri 10/15/10	Sat 10/30/10
16		Compile Capability Gaps/Needs from Literature Research	12 days	Fri 10/15/10	Sat 10/30/10
17		Establish Proposed Project Requirements and KPPs/KSAs	7 days	Fri 10/22/10	Sat 10/30/10
18		Conduct Requirements Trade-off Assessments	7 days	Sat 10/30/10	Sat 11/6/10
19		Verify Requirements to SME and Literature Research Gaps/Needs	6 days	Fri 11/5/10	Fri 11/12/10
20		Document Ranked Project Requirements and KPP/KSAs	12 days	Sat 10/30/10	Mon 11/15/10
21		Define Project Risks and Feasibility	9 days	Wed 11/10/10	Sat 11/20/10
22		Define Mission Capabilities and Operational Activities	19 days	Fri 10/15/10	Wed 11/10/10
23		Define Proposed Scenarios for System	17 days	Fri 11/12/10	Mon 12/6/10
24		Document Proposed Measures of Mission Success (MOE and MOP)	17 days	Fri 11/12/10	Mon 12/6/10
25		Establish Preliminary Final Report Outline	12 days	Fri 10/15/10	Sat 10/30/10
26		Conduct Interim Progress Brief #1 of 1 st QTR Work (Deliverable)	1 day	Mon 12/6/10	Mon 12/6/10
27		Conduct Functional Analysis & Verification Phase	91 days	Mon 12/6/10	Mon 4/11/11
28		Define Hierarchy and Decompose System Architecture	30 days	Mon 12/6/10	Fri 1/14/11
29		Document System Architecture into CORE	30 days	Mon 12/6/10	Fri 1/14/11
30		Identify System Interfaces/Assess Risks	11 days	Sat 1/1/11	Fri 1/14/11



Project: UUV_Schedule_11.04.19.
Date: Tue 4/19/11

Task		Project Summary		Inactive Milestone		Manual Summary Rollup		Deadline	
Split		External Tasks		Inactive Summary		Manual Summary		Progress	
Milestone		External Milestone		Manual Task		Start-only			
Summary		Inactive Task		Duration-only		Finish-only			

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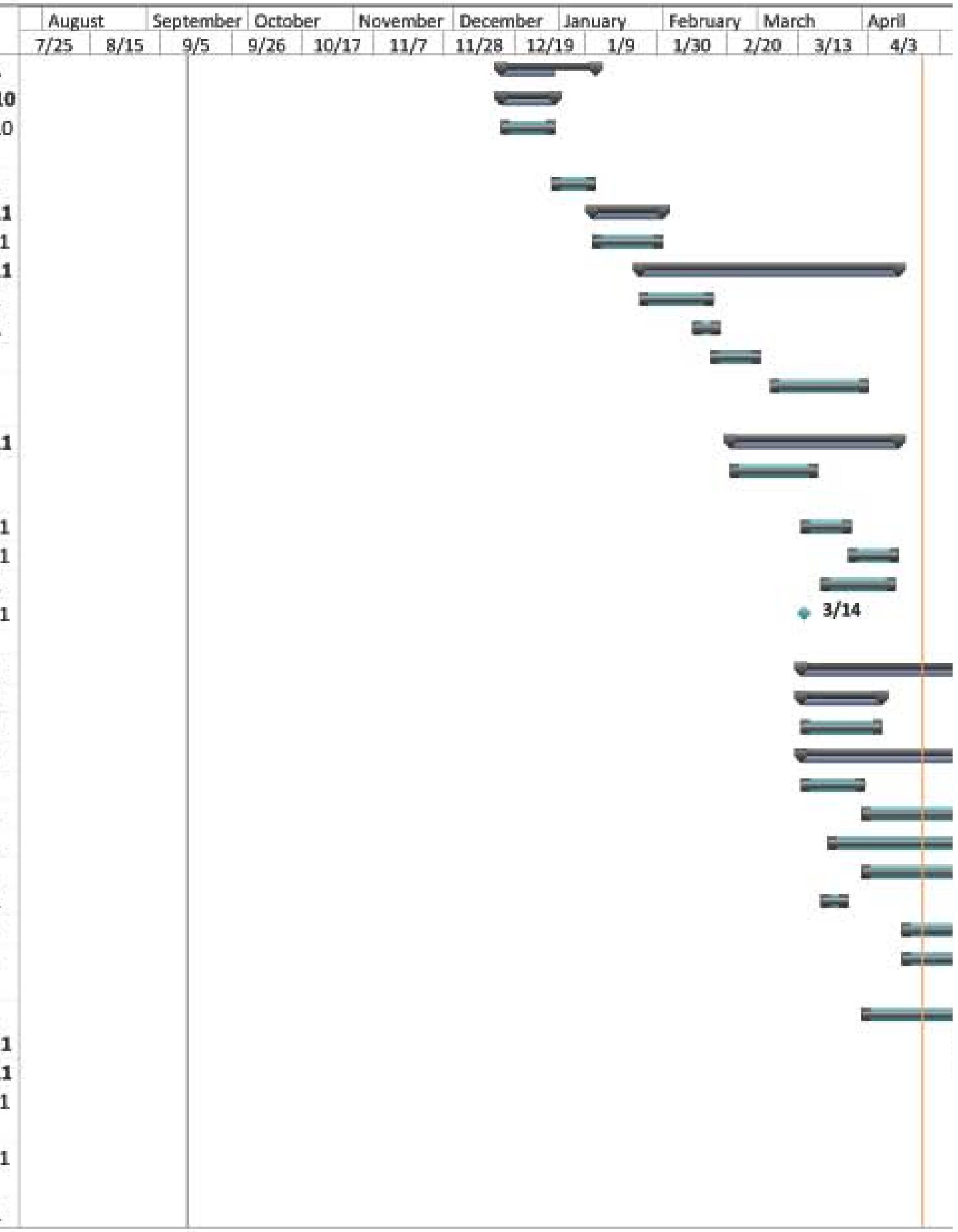
ID	Task Mode	Task Name	Duration	Start	Finish
31		Develop Functional and Behavioral Models of System	20 days	Wed 12/15/1(	Tue 1/11/11
32		Conduct Trade-offs of MOE & MOP	12 days	Wed 12/15/1(	Thu 12/30/10
33		Document Final MOE & MOP and Metric for Measurements	12 days	Wed 12/15/10	Thu 12/30/10
34		Verify MOE & MOP Support Stakeholder Needs	9 days	Thu 12/30/10	Tue 1/11/11
35		Using Top Level Architecture (Functions), Conduct QFDs	15 days	Tue 1/11/11	Mon 1/31/11
36		Document Alternatives (Morphological Matrix)	15 days	Tue 1/11/11	Mon 1/31/11
37		Conduct Scoring to Identify Top Alternatives	55 days	Tue 1/25/11	Mon 4/11/11
38		Conduct Design Trade-off Analysis and Assessments	16 days	Tue 1/25/11	Tue 2/15/11
39		Establish Value and Worth Scoring for Stakeholders	6 days	Thu 2/10/11	Thu 2/17/11
40		Define Concept Alternative Risks and Feasibility	11 days	Tue 2/15/11	Tue 3/1/11
41		Establish Life-Cycle Cost Estimates for Top Alternatives	22 days	Sat 3/5/11	Sat 4/2/11
42		Model and Simulate OPSITs for Alternatives	36 days	Mon 2/21/11	Mon 4/11/11
43		Determine MOE & MOP Measurements for Alternatives	20 days	Mon 2/21/11	Fri 3/18/11
44		Perform Modeling of Alternative Functions	11 days	Mon 3/14/11	Mon 3/28/11
45		Perform LRS Sensitivity Analysis	11 days	Mon 3/28/11	Mon 4/11/11
46		Conduct Team System Functional Review	17 days	Sun 3/20/11	Sun 4/10/11
47		Conduct Interim Progress Brief #2 of 2 nd QTR Work (Deliverable)	1 day	Mon 3/14/11	Mon 3/14/11
48		Conduct Design Synthesis & Verification	36 days	Mon 3/14/11	Sat 4/30/11
49		Conduct Cost-Benefit Analysis	18 days	Mon 3/14/11	Wed 4/6/11
50		Determine CAIV	18 days	Mon 3/14/11	Wed 4/6/11
51		Conduct Interface And Design Analysis	36 days	Mon 3/14/11	Sat 4/30/11
52		Develop Test Strategy	15 days	Mon 3/14/11	Fri 4/1/11
53		Develop Hardware/Software Integration Plan	22 days	Fri 4/1/11	Sat 4/30/11
54		Assess Safety and Usability	30 days	Tue 3/22/11	Sat 4/30/11
55		Assess Logistics Support	22 days	Fri 4/1/11	Sat 4/30/11
56		Conduct Reliability Analysis	7 days	Sun 3/20/11	Sun 3/27/11
57		Propose Final Design Recommendation	14 days	Wed 4/13/11	Sat 4/30/11
58		Validate Final Design Recommendation with Stakeholder Requirements	14 days	Wed 4/13/11	Sat 4/30/11
59		Determine Future Exploration Avenues	22 days	Fri 4/1/11	Sat 4/30/11
60		Project Conclusion	35 days	Sat 4/30/11	Wed 6/15/11
61		Complete Draft Final Report	23 days	Sat 4/30/11	Mon 5/30/11
62		Submit to SE Department Advisors and Secretary for Review (Deliverable)	1 day	Mon 5/16/11	Mon 5/16/11
63		Adjudicate Comments and Submit Final Project Report (Deliverable)	1 day	Mon 5/30/11	Mon 5/30/11
64		Develop Project Presentation	16 days	Mon 5/16/11	Mon 6/6/11



Project: UUV_Schedule_11.04.19.
Date: Tue 4/19/11

Task		Project Summary		Inactive Milestone		Manual Summary Rollup		Deadline	
Split		External Tasks		Inactive Summary		Manual Summary		Progress	
Milestone		External Milestone		Manual Task		Start-only			
Summary		Inactive Task		Duration-only		Finish-only			

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ID		Task Mode	Task Name	Duration	Start	Finish
65	✓		Deliver Project Presentation for Faculty and Stakeholders (Deliverable)	1 day	Mon 6/6/11	Mon 6/6/11

August September October November December January February March April

7/25 8/15 9/5 9/26 10/17 11/7 11/28 12/19 1/9 1/30 2/20 3/13 4/3

Project: UUV_Schedule_11.04.19.
Date: Tue 4/19/11

Task	Project Summary	Inactive Milestone	Manual Summary Rollup	Deadline
Split	External Tasks	Inactive Summary	Manual Summary	Progress
Milestone	External Milestone	Manual Task	Start-only	
Summary	Inactive Task	Duration-only	Finish-only	

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APPENDIX B – CONCEPTUAL ALTERNATIVE GENERATION

To support morphology and the eventual development of the components that made up to alternative systems examined in this report, technologies were envisioned for each component. Either these technologies could be known forms that perform similar functions necessary per QFD requirements or they could be ideas or concepts which may or may not come to fruition with research and development.

Using literature sources and experiences, the team generated at least two technology concepts for each of the eight (8) major components. Again, using judgment and experience, these technologies were ranked in the areas of "Cost/Schedule", Technological Maturity" and "Expected Performance" to assess the risks/impacts on a final concept which contained the technology. Text rankings were initially used; however, to eventually compare and contrast the technology alternatives for a given component, color coding of Green/Yellow/Red where used with Green being the best. This is because a technology could rank "Low" for Cost/Schedule and be considered beneficial, but also rank "Low" for Performance and be considered detrimental. The rankings were considered with respect to the other potential technologies within the same component group. For instance, a Carbon Steel structure is considered lower cost compared to a Titanium structure, which the actual cost in terms of dollars not considered. Whereas the actual dollar cost of the Carbon Steel structure would have been substantially more than the dollar cost of an Acoustic Homing Beacon.

The table that follows contains the technologies that were considered for each component package, the assessment of each technology alternative and the reasons behind the rankings received.

Table 1 – Technology Matrix

Major Component	Technology	Cost/ Schedule	Tech Maturity	Perform	Remarks	Ranking Reasoning
Support Structure	**Carbon Steel**	Low	Mature	Low	Heavy, corrosion, easy to work	Carbon steels are a low impact to cost/schedule because of their ample availability and established trade skill set in working with these materials. They are a mature technology and have been in use for many decades in submarine applications. Their performance is relatively low due to their corrosive nature when compared with readily available alloys.
	Monel	Medium	Mature	Medium	Heavy, dissimilar metal weld issues, costly	Due to longer lead times and expense in procurement of monel alloys, they are considered a medium risk to cost/schedule. However, the technological maturity is high because monel alloys have been used in submarine construction for many decades. Monel performance is ranked medium because it is preferred to carbon steel due to better corrosion resistance and superior strength qualities.
	Aluminum	Low	Mature	Low	corrosion, dissimilar metal issues	Aluminum is a readily available material so the cost and time to procure it is considered low. Aluminum has been available and used in various grades for decades so the technology is mature. The performance is ranked low due to known corrosion problems in seawater applications and the fact that welding aluminum to dissimilar is a complex process.
	Reinforced Carbon Fiber	High	Mature	Medium	structural strength issues, non-reactive, difficult to repair	Working with fiberglass is a prolonged process and the manpower required for fiberglass work is not normally found in shipbuilding industry so cost/schedule is considered high. Fiberglass work in recreational boating and automotive industries has been around for decades so the technology is considered mature. Performance is considered medium because of the non reactive-to-seawater property of it but fiberglass does not have the structural strength required for this application and it is difficult and time consuming to repair.
	Ceramics	High	Conceptual	High	non-reactive, difficult to repair	Ceramics are not normally used by the marine industry and especially in structural applications so the cost and schedule of procuring and working these materials is considered high. The use of ceramics has been around for centuries in pottery-like applications but the use of newer ceramic materials in industrial objects is still considered conceptual. Their performance is considered high because of their resistance to corrosion and relative light weight. However, although ceramics are strong in compression, they are weak in shearing and tension. Additionally they are difficult to repair.
	Titanium	High	Mature	High	corrosion, dissimilar metal issues	Titanium is a readily available material so the time to procure it is considered low but at a high cost. Titanium has been available and used in various grades for decades so the technology is mature. The performance is ranked high due to advantages in seawater applications; however, the fact that welding titanium to dissimilar is a complex process.

Major Component	Technology	Cost/ Schedule	Tech Maturity	Perform	Remarks	Ranking Reasoning
Recovery Mechanism	Divers	Low	Mature	Low	puts humans in danger, slow	Use of divers has virtually no impact to cost or schedule. Navy underwater divers have been employed in salvage and recovery operations since at least the late 19th century so this method of recovery is considered mature. Use of divers is considered a low performance ranking. It is not the preferred method of recovery due to the inherent danger associated with the operation and time required to deploy and retrieve the divers
	Articulated Mechanical Arm	Medium	Mature	Medium	slow, complex to operate, tube door open for extended period (ship safety)	Construction of an articulated mechanical arm poses the possibility of high cost and schedule impact due to complexity. The technology is mature in normal applications but use is limited in underwater applications due to electro-mechanical components. The performance is medium because their sluggish operation requires that outer tube doors remain open for extended periods.
	ROV	High	Prototype	High	(deploy homing ROVs which attach to UUV and direct back into tube), fast, more items to maintain	ROVs are a high impact to cost and schedule due to procurement of additional equipment required to procure and design storage for on the host platform. ROVs for this application would be considered a prototype meaning that the technology is there to build them but it has yet to be built which also add to the high cost/schedule ranking. Due to their high speed in retrieving the UUV, they are considered high in performance.
	Electro-mechanical Attraction Device	High	Prototype	High	fast, high power demand, could damage electronics, detectable by enemy	Electro-mechanical devices are basically a magnetic apparatus used to retrieve a UUV. Constructing this type of device would be cost prohibitive because of the power and shielding requirements. This device is considered a prototype due to the know-how is available and has been done before, but not for this application. The high speed of retrieving a UUV warrants a high performance ranking.
Launch Mechanism	Launch Ejection Gas Generator	Low	Mature	High	Current technology used on Strategic missiles so service proven	Because of their current use on Trident submarines, cost and schedule are considered low. Procurement of this equipment would be akin to an off-the shelf purchase. The technology is mature and has been in proven use since construction of Ohio class. The performance is high because of the speed at which the UUV could be launched and due to the relative low maintenance of the equipment. Using this alternative complies with commonality policy
	Release a catch (UUV "swims" away on its own)	Low	Mature	Medium	susceptible to ocean currents during launch	Release a catch allows a UUV to swim out of the tube under its own power. This is considered a low impact to cost/schedule since no additional equipment is required and a mature technology since existing UUV are currently operating on their own power. Potential issue with accidental contact with sub on recovery.
	Articulated Mechanical Arm	Medium	Mature	Medium	slow, complex to operate, tube door open for extended period (ship safety)	Construction of an articulated mechanical arm poses the possibility of high cost and schedule impact due to complexity. The technology is mature in normal applications but use is limited in underwater applications due to electro-mechanical components. The performance is medium because their sluggish operation requires that outer tube doors remain open for extended periods.

Major Component	Technology	Cost/ Schedule	Tech Maturity	Perform	Remarks	Ranking Reasoning
	Divers	Low	Mature	Low	puts humans in danger, slow	Use of divers has virtually no impact to cost or schedule. Navy underwater divers have been employed in salvage and recovery operations since at least the late 19th century so this method of recovery is considered mature. Use of divers is considered a low performance ranking. It is not the preferred method of recovery due to the inherent danger associated with the operation and time required to deploy and retrieve the divers
	ROV	High	Prototype	High	(deploy homing ROVs which attach to UUV and direct back into tube), fast, more items to maintain	ROVs are a high impact to cost and schedule due to procurement of additional equipment required to procure and design storage for on the host platform. ROVs for this application would be considered a prototype meaning that the technology is there to build them but it has yet to be built which also add to the high cost/schedule ranking. Due to their high speed in retrieving the UUV, they are considered high in performance.
	Electro-mechanical Repulsion Device	High	Prototype	High	fast, high power demand, could damage electronics, detectable by enemy	Electro-mechanical devices are basically a magnetic apparatus used to retrieve/repulse a UUV. Constructing this type of device would be cost prohibitive because of the power and shielding requirements. This device is considered a prototype based on the know-how is available and has been done before, but not for this application. The relative high speed of repulsing a UUV warrants a high performance ranking.
UUV Power and Re-Charging Mechanism	Batteries recharged on Host Sub (replaced on UUV while launched, by ROV or divers)	Low	Mature	Low	Divers would need to rendezvous with UUV and recharge it	Removal and replacement of existing batteries had no cost or schedule risk. The existing UUV batteries would be mature, and provide high performance. However, the issues involve with diver replacement are similar to that described for use in recovery.
	Undersea Recharging Docking Station	Medium	Prototype	Medium	Smaller Scale station used for REMUS	This was ranked medium on cost/schedule and performance, since the REMUS docking station could be considered a prototype. The ability to use it for a larger vehicle and different battery is what made it medium.
	Pulse Charge (while UUV launched)	High	Conceptual	Low	feasibility of doing this under sea from submarine not defined	High cost and performance issues equate to the pulse charge since it is conceptual.

Major Component	Technology	Cost/ Schedule	Tech Maturity	Perform	Remarks	Ranking Reasoning
	Charging pad (while UUV stowed)	High	Conceptual	High	based on electric car battery recharging system	Technology has not been demonstrated for cars. Undersea wireless communications issues have fidelity issues (thus the high cost and schedule risk). However, if successful, could support inductive charging at a distance and in wet environments.
	Host sub releases charging cable (while UUV launched)	Low	Mature	Medium	cable would be prone to flooding	Cost of cabling is low; technology is mature with external cables in use in several submarine systems; performance is medium because external cables are prone to flooding leaving them damaged. Dry charge would require a dry compartment, but would improve performance.
Stowage System	Catch/lock/clasp in payload tube	Medium	Mature	Medium	simple, potential for binding	Cost is medium due to additional hardware and heavy duty moving parts required; technology is medium; Performance is medium because this system will require the UUV to launch and recover under its own power.
	Canister that retracts into payload tube	High	Conceptual	Medium	would be part of the launch/recovery system	Cost is high due to additional hardware and complex precision heavy duty moving parts required; Conceptual technology in underwater applications; Performance is medium based on relative sluggish operation of moving .
	Magnet in payload tube	High	Prototype	High	large magnets would be costly	Cost is high based on large size of magnet required to retain a large UUV; Technology for magnets is mature (even large sizes) but are not in use for this system so prototype technology; performance is high because of low number of moving parts and clean installation.
	Sealed compartments in payload tube	Medium	Mature	High	each UUV would have designated stowage spaces	Cost is medium base on additional structural work required to create sealed compartments in the tube; Current shipbuilding practices could accommodate building of separate compartments; Performance is high because each UUV will have its own designated stowage area.
Control System Architecture	Portable plug-in control system	Low	Mature	Medium	A carry-on technology, not stored on board when subs mission doesn't require UUV operations	Cost is low because no additional space has to be designed into submarine to accommodate control system hardware; "Carry-On" hardware is currently employed on submarines so technology is mature; Performance is medium based on system not being fully integrated with sub and taking up space normally used by other equipment. Laptop would be designed to fit in 19 inch ranks

Major Component	Technology	Cost/ Schedule	Tech Maturity	Perform	Remarks	Ranking Reasoning
	Hardwired integrated system	Medium	Mature	Low	System becomes permanently part of the submarine's on-board systems	Cost of installing additional hardware/software into sub to accommodate control system is medium; Most systems on a sub are hardwired system so technology is very mature; Performance of a hardwired system is low because additional submarine space has to be found to accommodate control system hardware and potential interface performance issues.
	Wireless integrated system	Medium	Prototype	High	System becomes permanently part of the submarine's on-board systems	Cost of wireless is medium due to no cabling being required but still need space for hardware; Wireless technology is mature but few or no systems exist for this application so technology is prototype; Performance is high as there are no additional cables penetrating the hull which would be prone to cable flooding issues.
Communi-cations (docked or undocked), both RF and Acoustic to be considered	Radio frequency	Low	Prototype	High	Radio signal propagation is dependent on temperature, salinity, and depth. Usually difficult to transmit effectively underwater.	Cost of RF is medium due to no cabling being required but still need space for hardware; RF technology is mature but few or no systems exist for this application so technology is prototype; Performance is high as there are no additional cable penetrating the hull which would be prone to cable flooding issues.
	Hard-wired	Medium	Mature	Low	System becomes permanently part of the submarine's on-board systems	Cost of installing additional hardware/storage into sub to accommodate excess cabling is medium; hardwired technology is very mature; Performance of a hardwired system is low because additional submarine space has to be found to accommodate cabling plus it's impractical to the mission.
	Acoustic	Medium	Prototype	High	System becomes permanently part of the submarine's on-board systems. Subject to multi-path propagation, time variations of the channel and limited available bandwidth	Cost of acoustic system is medium due to no cabling being required but still need space for hardware; Acoustic technology is mature but few or no systems exist for this application so technology is prototype; Performance is high as there are no additional cables penetrating the hull which would be prone to cable flooding issues.

APPENDIX C – COST ANALYSIS WORKSHEETS

Acquisition cost considerations for conceptual alternatives were established by using cost data from internet and peer sources for exact or similar equipment. The tables established below provide the information the team used to arrive at the cost estimates for each alternative.

Overall Worksheet

Cost Category		QA	Engineering and Design	General And Administrative	Manufacturing/Installation	Program Management	Disposal	Material	Spare Parts	Total
	Mhr Rate	$ 85	$ 50	$ 80	$ 85	$ 80	$ 85	N/A	N/A	
Support Structure										
Option A: Carbon Steel	Man hours	200	1,500	375	2,000	200	350			4,625
	Cost	$ 17,000	$ 75,000	$ 30,000	$ 170,000	$ 16,000	$ 29,750	$ 1,200,000	$ 75,000	$ 1,612,750
Option B: Fiberglass	Man hours	200	1,500	375	2,000	200	350			4,625
	Cost	$ 17,000	$ 75,000	$ 30,000	$ 170,000	$ 16,000	$ 29,750	$ 12,040,000	$ 200,000	$ 12,577,750
Option C: Titanium	Man hours	250	1,500	375	2,000	200	350			4,675
	Cost	$ 21,250	$ 75,000	$ 30,000	$ 170,000	$ 16,000	$ 29,750	$ 5,400,000	$ 150,000	$ 5,892,000
Recovery Mechanism										
Option A: Articulated Mechanical Arm	Man hours	50	200	50	2,000	200	200			2,700
	Cost	$ 4,250	$ 10,000	$ 4,000	$ 170,000	$ 16,000	$ 17,000	$ 239,000	$ 2,000	$ 462,250
Option B: Remote Vehicle (ROV)	Man hours	50	200	50	2,000	200	200			2,700
	Cost	$ 4,250	$ 10,000	$ 4,000	$ 170,000	$ 16,000	$ 17,000	$ 165,000	$ 1,600	$ 204,250
Option C: Electro-mechanical Attraction Device	Man hours	15	150	37.5	1,200	120	200			1,723
	Cost	$ 1,275	$ 7,500	$ 3,000	$ 102,000	$ 9,600	$ 17,000	$ 27,000	$ 1,000	$ 123,375
Launch Mechanism										
Option A: Launch Ejection Gas Generator	Man hours	150	200	50	2,000	200	300			2,900
	Cost	$ 12,750	$ 10,000	$ 4,000	$ 170,000	$ 16,000	$ 25,500	$ 347,000	$ 75,000	$ 660,250
Option B: Release a catch	Man hours	20	100	25	200	50	50			445
	Cost	$ 1,700	$ 5,000	$ 2,000	$ 17,000	$ 4,000	$ 4,250	$ -	$ -	$ 33,950
Option C: Electro-mechanical Repulsion Device	Man hours	15	150	37.5	1,200	120	200			1,723
	Cost	$ 1,275	$ 7,500	$ 3,000	$ 102,000	$ 9,600	$ 17,000	$ 27,000	$ 5,000	$ 172,375
Power and Recharging Mechanism										
Option 1: Physical cable connection	Man hours	5	10	2.5	80	20	40			158
	Cost	$ 425	$ 500	$ 200	$ 6,800	$ 1,600	$ 3,400	$ 4,500	$ 1,000	$ 18,425
Option 2: Hostsub releases charging cable	Man hours	5	10	2.5	80	20	40			158
	Cost	$ 425	$ 500	$ 200	$ 6,800	$ 1,600	$ 3,400	$ 6,550	$ 1,000	$ 20,475
Option 3: Induction charging pad device	Man hours	5	20	5	80	20	40			170
	Cost	$ 425	$ 1,000	$ 400	$ 6,800	$ 1,600	$ 3,400	$ 11,050	$ 2,500	$ 13,625
Stowage System										
Option 1: Catch/lock/clasp in payload tube	Man hours	10	80	20	200	50	50			410
	Cost	$ 850	$ 4,000	$ 1,600	$ 17,000	$ 4,000	$ 4,250	$ 38,500	$ 4,500	$ 74,700
Option 2: Magnet in payload tube	Man hours	10	80	20	200	50	50			410
	Cost	$ 850	$ 4,000	$ 1,600	$ 17,000	$ 4,000	$ 4,250	$ 3,100	$ 1,500	$ 36,300
Option 3: Sealed compartments in payload tube	Man hours	20	80	20	200	50	50			420
	Cost	$ 1,700	$ 4,000	$ 1,600	$ 17,000	$ 4,000	$ 4,250	$ 55,000	$ 3,500	$ 32,550
Control System										
Option 1: Portable plug-in control system	Man hours	5	10	2.5	80	20	40			158
	Cost	$ 425	$ 500	$ 200	$ 6,800	$ 1,600	$ 3,400	$ 11,430	$ 1,500	$ 25,855
Option 2: Hardwired integrated system	Man hours	5	10	2.5	80	20	40			158
	Cost	$ 425	$ 500	$ 200	$ 6,800	$ 1,600	$ 3,400	$ 11,550	$ 1,500	$ 24,475
Radio Communication										
Radio frequency	Man hours	5	30	7.5	80	20	40			183
	Cost	$ 425	$ 1,500	$ 600	$ 6,800	$ 1,600	$ 3,400	$ 7,500	$ 1,500	$ 14,325
Acoustic Communication										
Acoustic	Man hours	5	40	10	80	20	40			195
	Cost	$ 425	$ 2,000	$ 800	$ 6,800	$ 1,600	$ 3,400	$ 19,180	$ 1,500	$ 15,025

Other Assumptions
1. For Manufacturing and Installation a man hour rate of $85/hr is assumed
2. For Engineering and Design a man hour rate of $50/hr is assumed
2. For General and Administrative a man hour rate of $80/hr is assumed
3. For every 4 hours of M & I, there is 1 hour of G & A

POWER AND RECHARGING

Option 1: Physical cable connection

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	Cable	$1,400	Similar VLS cabling/connectors	$1,400	$8,400
2	1	External Connector	$950	Similar VLS cabling/connectors	$950	$5,700
	1	Additional inboard cabling	$2,000	estimate	$2,000	$12,000
3	1	Internal Connector	$200	Similar VLS cabling/connectors	$200	$1,200
				Total:	**$4,550**	**$27,300**

Option 2: Hostsub releases charging cable

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	Cable	$1,400	Similar VLS cabling/connectors	$1,400	$8,400
2	1	External Connector	$950	Similar VLS cabling/connectors	$950	$5,700
	1	Additional inboard cabling	$2,000	estimate	$2,000	$12,000
	1	Internal Connector	$200	Similar VLS cabling/connectors	$200	$1,200
3	1	Cable release mech	$2,000	estimate	$2,000	$12,000
				Total:	**$6,550**	**$39,300**

Option 3: Induction charging pad device

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	Cable	$1,400	Similar VLS cabling/connectors	$1,400	$8,400
2	1	External Connector	$950	Similar VLS cabling/connectors	$950	$5,700
	1	Additional inboard cabling	$2,000	estimate	$2,000	$12,000
	1	Internal Connector	$200	Similar VLS cabling/connectors	$200	$1,200
3	1	Charging Pad	$6,500	estimate	$6,500	$39,000
				Total:	**$11,050**	**$66,300**

LAUNCH MECHANISM

Option 1: Launch Ejection Gas Generator

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	Gas Generator	$250,000	estimate	$250,000	$1,500,000
2	1	Associated Piping	$75,000	estimate	$75,000	$450,000
3	1	Control System	$22,000	estimate	$22,000	$132,000
				Total:	**$347,000**	**$2,082,000**

Option 2: Release a Catch

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1					$0
2	1					$0
3	1					$0
				Total:	**$0**	**$0**

Option 3: Electro Mechanical Repulsion Device

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	motor-generator	$20,000	similar shipboard models	$20,000	$120,000
2	1	cables/wire/coil	$4,000	estimate	$4,000	$24,000
3	1	core material	$3,000	estimate	$3,000	$18,000
				Total:	**$27,000**	**$162,000**

RECOVERY MECHANISM

Option 1: Articulated Mechanical Arm

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	Articulating Arm	$225,000	estimate	$225,000	$1,350,000
2	1	Software	$4,000	estimate	$4,000	$24,000
3	1	Control System	$10,000	estimate	$10,000	$60,000
				Total:	**$239,000**	**$1,434,000**

Option 2: Remote Vehicle (ROV)

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	ROV	$125,000	price scaled based on smaller ROVs	$125,000	$750,000
2	1	ROV Control System	$15,000	estimate	$15,000	$90,000
3	1	ROV Storage	$25,000	estimate	$25,000	$150,000
				Total:	**$165,000**	**$990,000**

Notes: 1. smaller ROVs price around $15,000 - $20,000

Option 3: Electro-mechanical Attraction Device

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	motor-generator	$20,000	similar shipboard models	$20,000	$120,000
2	1	cables/wire/coil	$4,000	estimate	$4,000	$24,000
3	1	core material	$3,000	estimate	$3,000	$18,000
				Total:	**$27,000**	**$162,000**

Notes: 1. If ship's diesel generator is used to provide current to the coil, a separate generator is unnessary.

CONTROL SYSTEM

Option 1: Portable plug-in control system

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	Cable to TR	$1,400	Current VLS weapon control cable	$1,400	$8,400
2		Pigtail to laptop	$600	estimate		
3	1	External Connector	$950	Current VLS outboard 30-pin connector	$950	$5,700
4	1	Internal Connector	$200	Current VLS inboard connector	$200	$1,200
5	1	Carry-on Laptop	$3,880	Getac V200 rugged tablet PC http://ruggednotebooks.com/getac-v200-fully-rugged-convertible-tablet-laptop	$3,880	$23,280
6	1	Software	$5,000	high-end custom software similar costs	$5,000	$5,000
				Total:	**$11,430**	**$43,580**

Note: Total software cost based extending software license to six systems

Option 2: Hardwired control system

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	Cable	$1,400	Current VLS weapon control cable	$1,400	$8,400
2	1	External Connector	$950	Current VLS outboard 30-pin connector	$950	$5,700
3	1	Additional inboard cabling	$2,000	estimate		
4	1	Internal Connector	$200	Current VLS inboard connector	$200	$1,200
5	1	Computer	$4,000	estimate	$4,000	$24,000
6	1	Software	$5,000	high-end custom software similar costs	$5,000	$5,000
				Total:	**$11,550**	**$44,300**

Notes:
1. Total software cost based extending software license to six systems
2. Computer will be installed in existing fire control console in Control resulting in a dual purpose station
3. Additional inboard cabling will be from hull penetration to Control

SUPPORT STRUCTURE

Options 1, 2 & 3:

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	Carbon Steel Support Structure	$1,200,000	carbon steel price expressed as cost of qty. (1) MAC structure	$1,200,000	$7,200,000
2	1	Titanium Support Structure	$12,040,000	titanium price expressed as a percentage of qty. (1) MAC structure	$12,040,000	$72,240,000
3	1	Carbon Fiber Support Structure	$5,400,000	Carbon Fiber price expressed as a percentage of qty. (1) MAC structure	$5,400,000	$32,400,000
				Total:		

Notes:
1. Based on current cost of SSGN/SSN Multiple All-Up Cannisters (sourced through Electric Boat)
2. carbon steel price estimated using current $US/ton (http://www.meps.co.uk/world-price.htm) ($0.40/lb or $815/ton)
3. titanium prices obtained from http://www.metalprices.com/freesite/metals/ti_product/ti_product.asp (approx $7.00/lb or $22,300/ton)
4. carbon fiber price obtained from http://www.compositesworld.com/news/doe-advances-lower-cost-carbon-fiber-rampd ($8/lb or $16,000/ton)
5. **$2,000,000** MAC price obtained from EB (Cathy Innes)
6. MAC materials consist of various steels (HY, stainless, etc)

Material	Density (g/cm3)	Density (lb/ft3)	$/lb	$/system	Pounds	Volume
Carbon Steels	7.85 g/cm3	490	$ 0.40	$ 1,200,000	3000000	6122.449
Titanium	4.506 g/cm3	281	$ 7.00	$ 12,042,857	1720408	6122.449
Carbon Fibers	1.78 g/cm3	111	$ 8.00	$ 5,436,735	679592	6122.449

STOWAGE MECHANISM

Option 1: Catch/lock/clasp in payload tube

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	additional hydraulic piping	$2,500	estimate	$2,500	$15,000
2	1	hydraulic actuator	$6,000	based on VLS fairing locking cylinder	$6,000	$36,000
3	1	locking mechanism	$30,000	based on VLS fairing locking mechanism	$30,000	$180,000
				Total:	**$38,500**	**$231,000**

Notes: 1. Used APL for locking cylinder and locking mechanism to obtain actual costs

Option 2: Magnet in payload tube

ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	Samarium Cobalt Magnet (2"x26")	$1,100	$/lb of a SmCo magnet	$1,100	$6,600
2	1	Installation hardware	$2,000	estimate	$2,000	$12,000
				Total:	**$3,100**	**$18,600**

Notes:
1. According to http://www.magnetshop.com/materials.html, Samarium Cobalt (SmCo) is a suitable magnet material for advanced technical applications.
2. SmCo cost is approx $70/lb
3. Density of SmCo 0.3 lbs/in3
4. Assume a 2" thk x 26" dia (arbitrary diameter chosen) = 52 in^3 = 15.6 lbs = $1,100

Option 3: Sealed compartments in payload tube

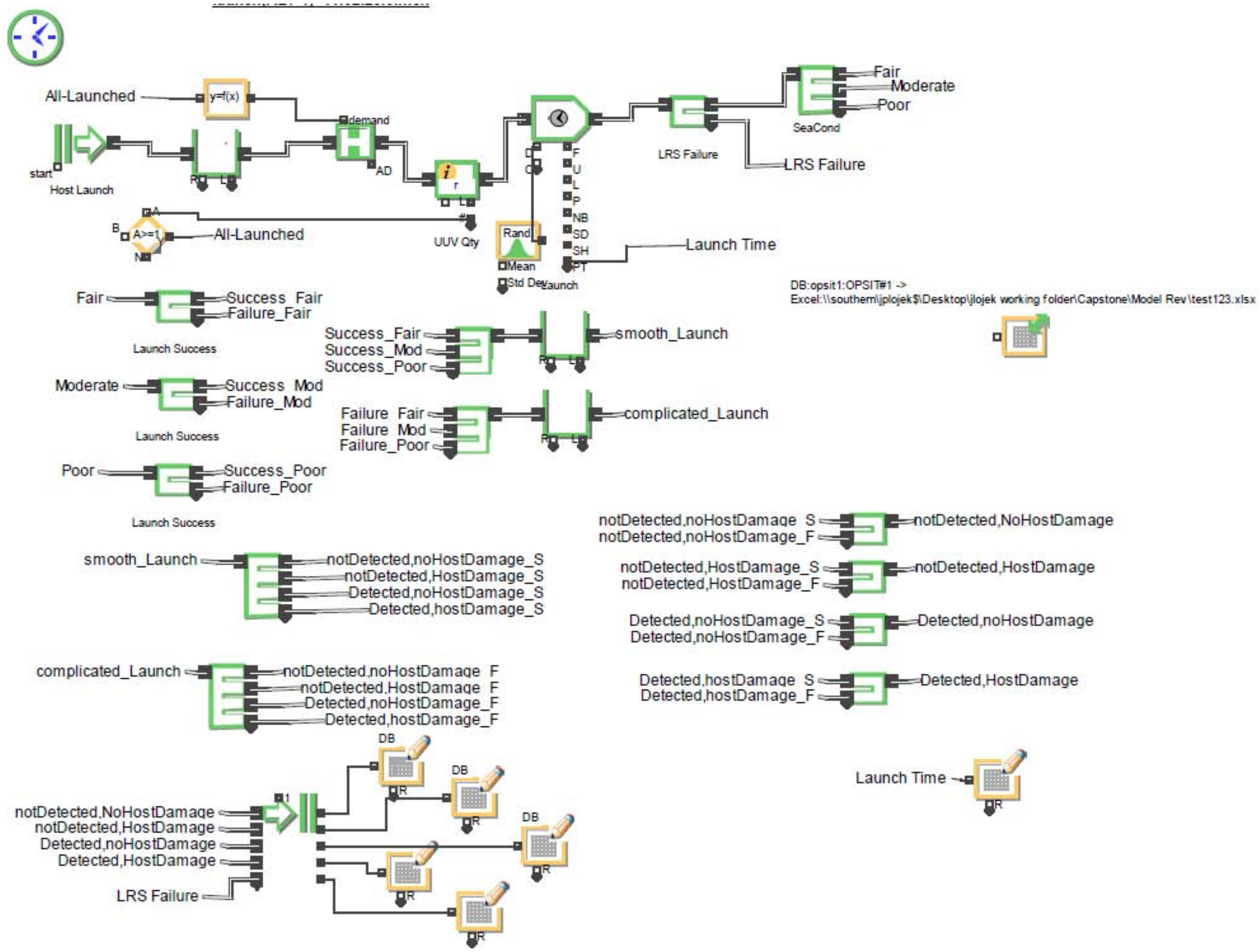
ITEM	QTY.	DESCRIPTION	COST	ESTIMATE BASED ON	TOTAL FOR ONE SYSTEM	TOTAL FOR SIX SYSTEMS
1	1	additional structure to accommodate seals	$35,000	estimate	$35,000	$210,000
2	1	sealing hatches	$20,000	estimate	$20,000	$120,000
				Total:	**$55,000**	**$330,000**

RADIO COMMUNICATION						
ITEM	**QTY.**	**DESCRIPTION**	**COST**	**ESTIMATE BASED ON**	**TOTAL FOR ONE SYSTEM**	**TOTAL FOR SIX SYSTEMS**
1	1	transmitter/amplifier	$5,000	estimate	$5,000	$30,000
2	1	receiver	$2,500	estimate	$2,500	$15,000
				Total:	**$7,500**	**$45,000**
Notes:	1. Assumed a basic radio system that could be used to send a signal to the LRS from inside the host sub					

ACOUSTIC COMMUNICATION						
ITEM	**QTY.**	**DESCRIPTION**	**COST**	**ESTIMATE BASED ON**	**TOTAL FOR ONE SYSTEM**	**TOTAL FOR SIX SYSTEMS**
1	1	Laptop with preinstalled HAIL (Hydro Acoustic Information Link) software & modem	3880 + $15,000	Getac V200 rugged tablet PC http://ruggednotebooks.com/getac-v200-fully-rugged-convertible-tablet-laptop	$18,880	$113,280
2	1	power supply	$300	estimate	$300	$1,800
				Total:	**$19,180**	**$115,080**
Notes:	1. Based estimates on of L3 HAIL system (http://www.l-3com.com/nautronix/products/pdf/NMS-C-SS-002HydroAcousticInformationLinkSpecificationSheetR2.pdf)					

APPENDEX D – FUNCTIONAL MODELING

A. LAUNCH MODEL



The launch model simulated 1000 LRS launches for each alternative and its results are provided in Table A (in this Appendix). Each launch was independent of the previous launch and independent of the three remaining system functions: Recovery, Maintain and Replenish. Launch condition were described as Fair, Moderate or Poor, and each expressed with a constant likelihood. Launch condition parameters were not variable and remained fixed for all launch simulations. The modeling parameters identified in Table 19 of the report were used for Launch Modeling. The likelihood of a Smooth or Complicated Launch was dependent on the launch condition of Fair, Moderate or Poor. The likelihood of success is more probable during a smooth launch than a complicated launch and was defined as Not Detected and No Damage. The parameters used for defining the likelihoods leading to success are described in Table A. All simulations results were outputted to a Microsoft Excel spreadsheet where a descriptive analysis was performed to evaluate the performance of the launch function.

Table A - Launch Model Raw Data

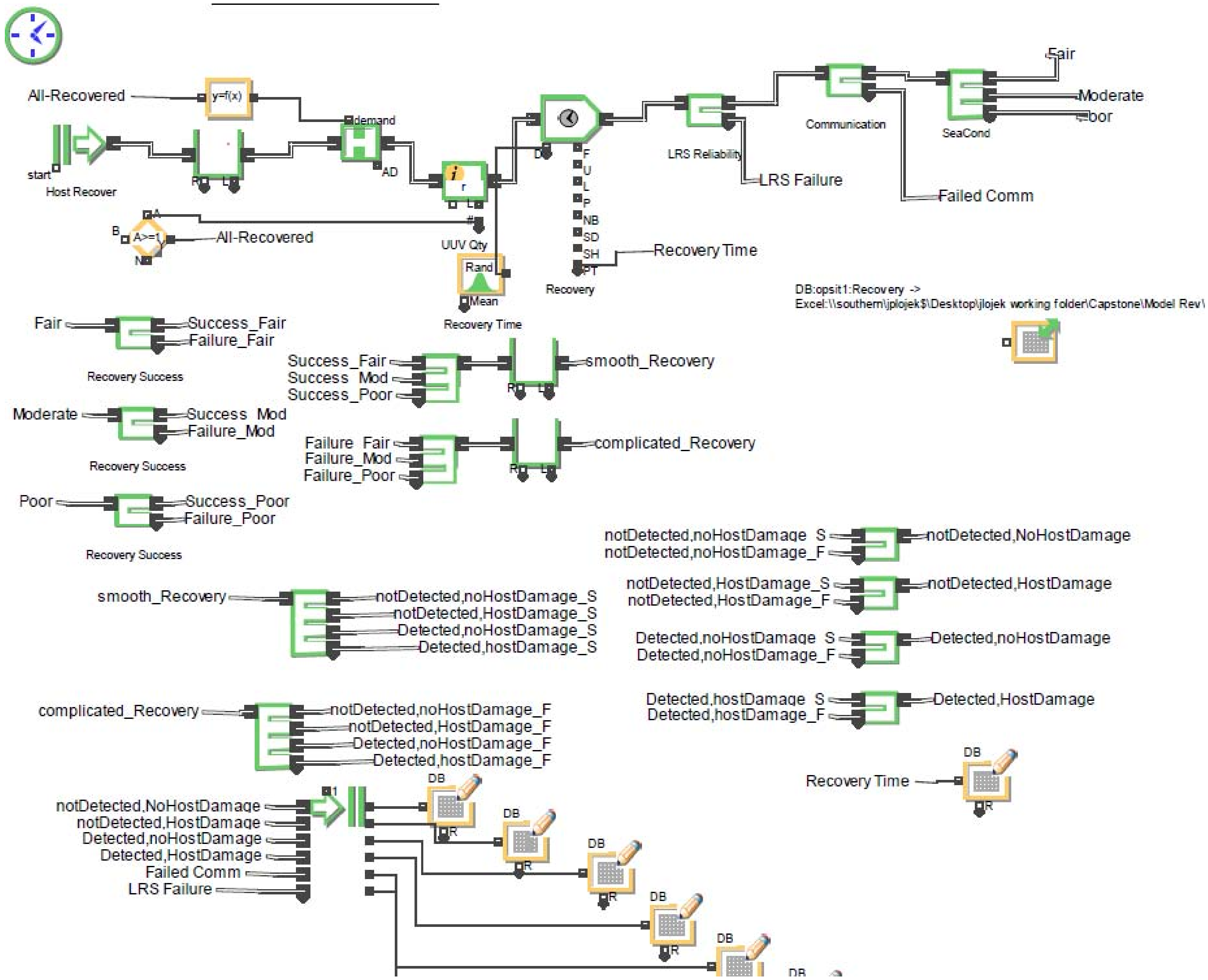
Launch Model Raw Data

	Not Detected & No Host Damage	Not Detected & Host Damaged	UUV Detected & No Host Damage	UUV Detected & Host Damaged	LRS Success	Launch Time [min]
Alt-1	90.3%	2.5%	1.8%	3.8%	98.4 %	11.25
Alt-2	85.4%	2.5%	2.5%	6.8%	97.2 %	11.25
Alt-3	89.4%	4.0%	0.6%	5.2%	99.2 %	11.33
Alt-4	90.1%	2.1%	1.1%	4.7%	98.0 %	12.84
Baselin e	81.5%	3.4%	3.2%	8.9%	97.0 %	14.97

Table B - Launch/Recovery Likelihoods in Varying Conditions

	Baseline	Alt 1	Alt 2	Alt 3	Alt 4
Smooth Launch in Fair Condition	93.00%	97.00%	95.00%	96.00%	97.00%
Smooth Launch in Moderate Condition	90.00%	94.00%	92.00%	93.00%	94.00%
Smooth Launch in Poor Condition	80.00%	84.00%	82.00%	83.00%	84.00%
Smooth Launch: No Damage & Not Detected	92.00%	96.00%	94.00%	95.00%	96.00%
Smooth Launch: No Damage & Detected	3.50%	2.00%	3.50%	3.50%	3.00%
Smooth Launch: Damaged & Not Detected	3.00%	1.50%	1.50%	1.00%	0.75%
Smooth Launch: Damaged & Detected	1.50%	0.50%	1.00%	0.50%	0.25%
Complicated Launch: No Damage & Not Detected	1.50%	0.50%	1.00%	0.50%	0.25%
Complicated Launch: No Damage & Detected	3.00%	1.50%	1.50%	1.00%	0.75%
Complicated Launch: Damaged & Not Detected	3.50%	2.00%	3.50%	3.50%	3.00%
Complicated Launch: Damaged & Detected	92.00%	96.00%	94.00%	95.00%	96.00%
Expected Likelihood of Successful Launch (No Damage & Not Detected)	86.07%	92.69%	89.35%	90.77%	92.45%

B. RECOVERY MODEL



The Recovery Model is nearly identical to that used to evaluate the performance of launching utilizing the parameters identified per

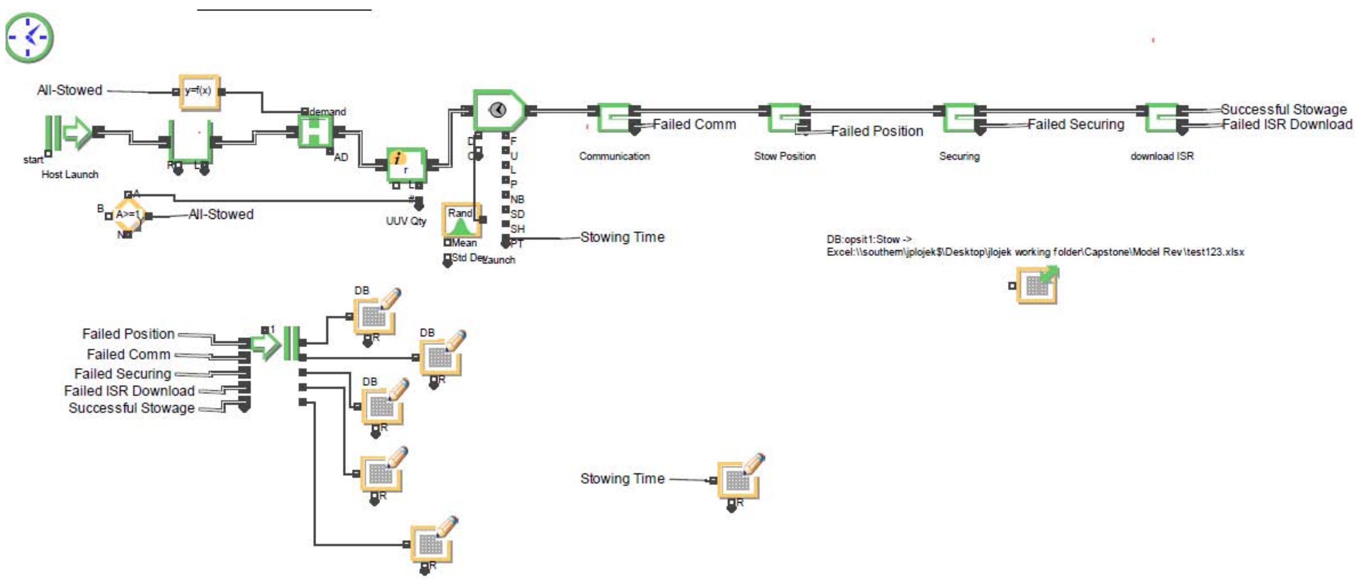
Table 19 of the report and Table B and simulated 1000 recoveries. Raw data of each alternative model is provided in Table C. A new variable was added to model the likelihood of communication linkage of the host platform and returning UUV for retrieval. Failed communication link would ultimately result in a failed attempt to recovery the UUV. If communications is successful the same order of events and likelihoods described in the launch procedure are followed. Although each design concept shared similar communication systems it was assumed that the LRS structural material and placement of communication devices would vary the likelihood of success for establishing a communication linkage during recovery. This variation was captured in the likelihood of communication success in Table 19 of the report. All results from the 1000 LRS recoveries were data-based to a Microsoft Excel spreadsheet where they were analyzed to evaluate recovery performance of the baseline and four alternatives.

Table C - Recovery Model Raw Data

Recovery Model Raw Data

	Failed Communications	Not Detected & No Host Damage	Not Detected & Host Damaged	UUV Detected & No Host Damage	UUV Detected & Host Damaged	LRS Success	Recovery Time [min]
Alt-1	1.8%	88.7%	2.0%	2.0%	3.5%	98.0%	25.63
Alt-2	0.5%	86.6%	3.4%	1.1%	5.8%	97.4%	30.05
Alt-3	0.8%	87.7%	3.3%	1.1%	5.7%	98.6%	26.95
Alt-4	2.9%	87.2%	2.7%	1.1%	4.6%	98.5%	25.47
Baseline	1.0%	81.0%	3.3%	2.6%	8.1%	96.0%	37.45

C. MAINTAIN MODEL



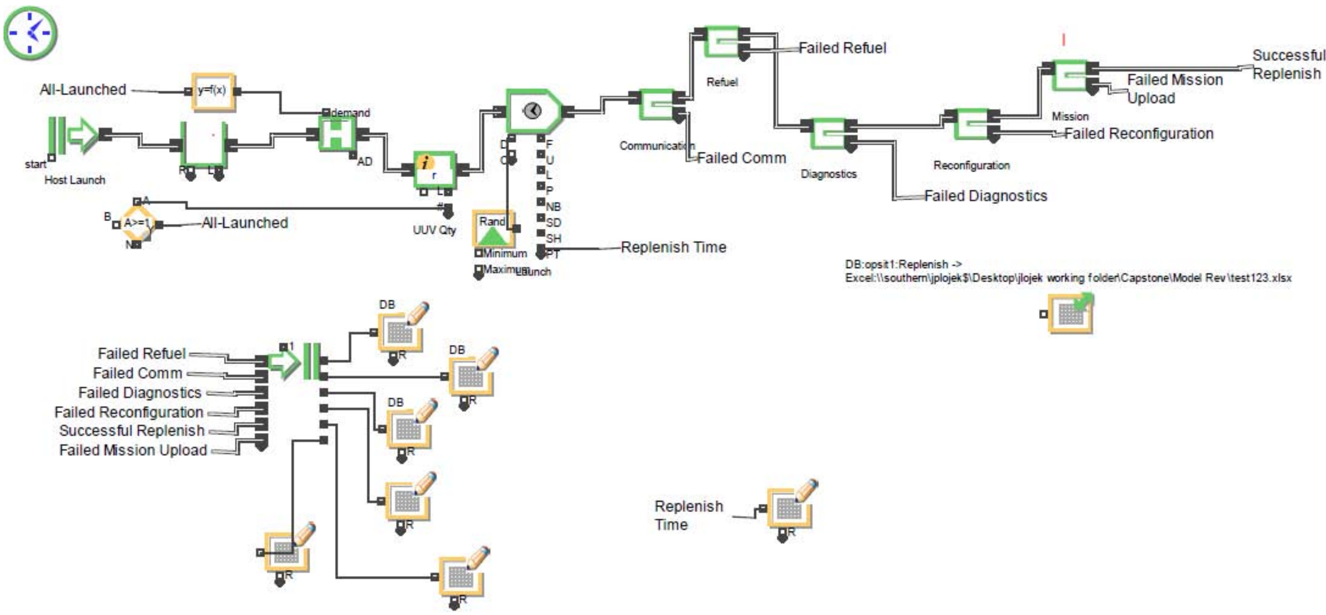
The Maintain model captured the performance of the baseline and alternatives to successfully stow once recovered and successfully mount within the payload tube for 1000 cycles. The results of the simulation for each alternative are provided in Table D. Once successfully stowed the LRS is then able to initiate UUV maintain procedures. The definition of success for maintaining is dependent on successful: ISR data retrieval, securing UUV in payload tube, LRS positioning UUV for securing, and communication between the LRS and host platform. The variable used to simulate each design concept can be found in Table 19 - Concept Alternative Modeling Parameters. Unlike launch and recovery models, maintain procedures are internal to the host platform and therefore are not functions of varying sea conditions.

Table D - Maintain Model Raw Data

Maintain Model Raw Data

	Failed Positioning	Failed Communication Link	Failed UUV Securing	Failed ISR Data Download	Successful Maintain	Stowage Time [min]
Alt-1	1.4%	1.1%	0.6%	0.1%	96.8%	12.04
Alt-2	0.8%	0.6%	0.2%	0.2%	98.2%	11.99
Alt-3	1.4%	1.0%	0.1%	0.4%	97.1%	12.22
Alt-4	1.4%	1.6%	0.6%	0.3%	96.1%	10.98
Baseline	0.8%	1.5%	0.9%	0.1%	96.7%	15.07

D. REPLENISH MODEL



The replenish model was simulated to represent 1000 replenish cycles and Table E provides the raw data to each alternative simulation. The parameters used for modeling are identified per were Table 19 - Concept Alternative Modeling ParametersTable 19 - Concept Alternative Modeling Parameters. The replenish model was independent of all other models (Launch, Recovery, and Maintain) and success is defined by successfully: establishing communication between Host/LRS/UUV, refueling UUV, diagnosing LRS/UUV system, reconfiguring system with software updates and uploading future mission data. All data was collected in a Microsoft Excel data-base that was analyzed with descriptive statistics to evaluate replenishment performance.

Table E - Replenishment Model Raw Data

Replenishment Model Raw Data

	Failed Communication Link	Failed Re-Charging	Failed Diagnostics	Failed Reconfiguration	Failed Mission Upload	Successful Replenish	Replenish Time [hour]
Alt-1	1.3%	1.6%	1.9%	1.4%	0.8%	93.0%	45.55
Alt-2	0.4%	2.6%	1.7%	0.4%	0.6%	94.3%	45.54
Alt-3	1.4%	2.4%	1.2%	1.5%	1.1%	92.4%	45.55
Alt-4	1.8%	3.4%	1.4%	1.0%	1.3%	91.1%	43.70
Baseline	1.7%	1.3%	1.9%	0.9%	0.6%	93.6%	45.56

APPENDEX E – TEST AND EVALUATION STRATEGY

PART I – INTRODUCTION

1.1. Purpose. The Test and Evaluation Strategy (TES) provides an overview into testing at various phased of design and production for the Launch and Recovery System (LRS).

1.2. Mission Description. For submarine launched UUVs to be an effective tool for undersea warfare persistent-ISR operations, a system is required to integrate the host submarine and the Large Vehicle Class UUVs. This system must provide launch, recovery, replenishment and communication capabilities without adversely affecting the certification of the host submarine for unrestricted operations.

1.3. System Description. The LRS system has 8 major components: Support Structure, Recovery Mechanism, Launch Mechanism, UUV Recharging Mechanism, UUV Stowage System, Launch and Recovery Control System Architecture, Short-Range RF Communications, and Acoustic Homing Communications. There are 5 top concept alternatives developed which provide various combinations of alternatives for the major components. Support Structure will be either carbon steel, titanium or composite. The Recovery Mechanism has 4 options: Swim to Cradle, Electro-Mechanical Device, Articulated Mechanical Arm, or a Tethered Remote Vehicle. The Launch Mechanism has three options: Swim Away, Pressurized Gas Ejection or an Electro-Mechanical Device. The UUV re-charging Mechanism supports three options, all with the UUV in the stowed position: a Wet Cable Connection, Dry Cable Connection or an Inductive Charging Method. The UUV stowage system also has three alternative options in: Mechanical Locks, Sealed/Dry Compartments in the Payload Tube or Magnetic Locks. The Launch and Recovery Control Arm System Architecture has been chosen to be a Portable, Plug-in Control Hardware/Software. The Short-Range RF Communications component will utilize underwater radio waves. The Acoustic Homing Communications will use an Acoustic Homing Beacon.

1.3.1. System Threat Assessment. The LRS will contend with threats in all phases of use, from accidental damage during the loading operations and/or transport to detection by enemy sonar and radars leading to torpedo and missile attack as well as risk of accident as the UUV movement and operability is affected by ocean currents/tides and unwanted detection of acoustic communication leading to compromise of the UUV and host submarine assets. Threats during data transfer also include active and passive enemy detection capabilities requiring a level of encryption and security that may further inhibit timely information transfer.

1.3.2. Program Background. From the component matrix, five leading concepts were chosen as the most likely concepts meeting the requirements of the LRS. Since components are in various stages of technological development, components will require varied levels of developmental testing to ensure that each concept/prototype has adequate technology, when integrated to meet system requirements.

1.3.3. Key Capabilities. The LRS will provide a launch, recovery, storage and recharging mechanism for long range ISR type UUVs. Key Performance Parameters (KPPs) have been identified for the LRS, which will be used in the testing phases to ensure the developed system meets stakeholder needs. These KPPs are: safe operation, affordability, reliability, communication success, flexibility, launch success and recovery success.

1.3.3.1. Key Interfaces. The LRS has direct interfaces with the VIRGINIA Block III host submarine as well as the ISR UUV.

1.3.3.2. Special Test Requirements. At this time, no unique testing requirements are identified for the LRS.

1.3.3.3. Systems Engineering (SE) Requirements. The SE approach for the LRS focuses on concept development and exploration of alternate solutions at various early acquisition stages. The requirements definition phase does not rule out technologies nor does it force the solution to a specific development effort. Once the system and physical architecture were defined, component areas were identified and could initially be compared to similar components with various Technology Readiness Levels. The beginning stages of design synthesis (concept design) identified top conceptual alternatives. The options for each alternative began to identify possible technologies to be developed and tested. Once the down select to one concept design to begin preliminary design happens, component alternatives for the concept will be evaluated and developmental testing will be further defined.

PART II – TEST and EVALUATION PROGRAM MANAGEMENT AND SCHEDULE

2.1. T&E Management. The contractors developing the prototypes are responsible for the majority of developmental testing, however, the government is required to approve the test procedures for selected developmental tests. The government will conduct fully integrated operational testing with the contractor on hand as a witness and to troubleshoot any problems. Technology Readiness Levels determined by the contractor shall be verified through the Office of Naval Research.

2.2. T&E Data Strategy. Data collection for LRS testing will include modeling and simulation data recording successful/safe launch and recovery operations, using enough modeling and simulation runs to provide 95 percent confidence that the developed system will meet its performance requirements. Weight data will be taken by calibrated load cells to determine overall system weight and impact on host ship. Acoustic monitoring devices will record radiated noise from LRS operations. Data transfer rate and security will be monitored and recorded to maintain minimum data transfer rate levels.

2.3. Integrated Test Program Schedule. Competitive prototypes for the LRS are not required. The downselect for a single concept will be based on the cost and capability analysis of the chosen alternatives. Once the concept baseline has been chosen, detail design and testing will commence. The project is too early in development to discuss testing schedules; however, certain tests have been identified: bench tests on launch, recovery and stowage actuators, bench tests on communications devices, component weight measurements and integration testing for the control architecture as well as LRS functionality in a non installed payload tube. All required SUBSAFE testing and necessary OQE will also be required.

PART III – TEST AND EVALUATION STRATEGY

3.1. T&E Strategy Introduction. At the preliminary design phase, the Test and Evaluation Strategy mimics the Test Program Schedule – bench testing on the component level and integration testing on the system level. All components that are identified as SUBSAFE will have appropriate SUBSAFE testing and documentation integrated into the test schedule. Each identified interface for the LRS will be evaluated to ensure all requirements of the ICD are met.

3.2. Evaluation Framework. Early stage testing will emphasize the evaluation of components and concepts to determine the best performers and allow insight into possible combinations of components for superior performance. Each component or sub-system will be evaluated for reliability and performance values based on the functions each component/sub-system performs. The testing will provide validation for our component selection and the concept modeling and simulation output. As the concepts mature and a prototype is chosen, system integration testing is performed based on the outlined mission scenarios. This testing measures concept/prototype performance against required values.

3.3. Developmental Evaluation Approach. All selected component options will be developed and tested to meet the requirements of the functions they perform. Component testing shall be designed to compare components performance and reliability on each function to which the component is mapped.

3.3.1. Developmental Test Objectives. Once a concept is selected, developmental items will be identified. Technology Readiness Levels will be assessed and development will be directly influenced by LRS mission specific requirements. To accelerate component development, testing will reflect LRS specific mission requirements instead of generic functional requirements. For example, the UUV stowage system development will have design and testing based on the specific constraints of the LRS program (VIRGINIA Block III specific constraints).

3.3.2. Modeling & Simulation (M&S). Early stage modeling and simulation was used to select concept alternatives. The LRS is a mechanical system and limited, if any modeling and simulation will be required for follow on testing once a component baseline is selected. All components can be mechanically or electrically tested in their environment or simulated environment.

3.3.3. Test Limitations. With a specific concept chosen, testing will be based on each component's function within the LRS. Issues with future integration into the LRS system will arise if the interfaces between components are not clearly defined. An emphasis on proper interface definition will enable developmental testing of interfaces and reduce integration issues. We do not foresee limitations with developmental testing.

3.4. Operational Evaluation Approach. When a leading concept is selected from the top alternatives, a more refined operational evaluation (OPEVAL) will be established. The main approach will be to satisfy the identified OPSITS chosen as representative missions for the LRS. Personnel will require training with the LRS to launch, recover, replenish and maintain the LRS prior to OPEVAL.

3.4.1. Mission-Oriented Approach. As the LRS is limited in external interfaces (host submarine and UUV), only two phases of operational testing has been identified at this time. A LRS will be installed into a test payload tube with a remote control station and conduct submerged launch and recovery operations on the UUV. For the 2nd phase of operational testing, the fully functioning LRS will be installed on a VIRGINIA Class Block III submarine and run through full launch and recovery operations. Successful completion of Phase I will give the green light for Phase II. If Phase I is unsuccessful, redevelopment of the LRS will commence. Phase II can only begin upon successful completion of Phase I.

3.4.2. Operational Test Objectives. A full theater will be developed to provide realistic environments for the stated OPSITS. The LRS will progress through each OPSIT being evaluated against the identified KPPs in each OPSIT.

3.4.3. M&S. Early stage modeling and simulation was used to select concept alternatives. The LRS is a mechanical system and limited, if any modeling and simulation will be required for follow on testing. All components can be mechanically or electrically tested in their environment or simulated environment.

3.4.4. Test Limitations. No operational test limitations are foreseen at this stage of preliminary design. If a component cannot be tested in its direct environment, a sufficient environment can be provided to simulate the actual working environment.

3.5. Future Test and Evaluation. No future testing has been identified. Developmental and Operational Tests will be expanded upon once a single concept is selected and interfaces are refined with concept specific parameters.

PART IV – RESOURCE SUMMARY

4.1. Introduction. Testing will take full advantage of existing DoD ranges, facilities, and other resources wherever practical. Hydrostatic testing of larger components or prototypes required to withstand test depth can be tested at NSWCCD or a test tank in Annapolis, Md.

4.1.1. Test Articles. The first stage if integrated testing will involve a VIRGINIA Class Block III Payload Tube (not integrated into submarine), a test facility with sufficient depth to conduct UUV launch and recovery operations, 3 nominally sized ISR UUVs, and a mockup of the LRS control station. Full system integration testing will require a dedicated VIRGINIA Class Block III submarine with an available payload tube, a LRS fully outfitted into the host sub, 3 nominally sized ISR UUV's, sufficient water depth to conduct ISR operations and required support vehicles as well as divers in the water to observe launch and recovery operations.

4.1.2. Test Sites and Instrumentation. No specific test ranges have been identified; however, the selected site will have to provide an ideal radiated noise testing environment as well as sufficient depth to conduct UUV launch and recovery operations. Water clarity must be sufficient to allow video documentation of launch and recovery operation.

4.1.3. Test Support Equipment. Underwater radiated noise equipment and testing personnel must be available to record noise levels associated with operation of LRS system. Equipment and personnel (divers) to support underwater video documentation of the LRS operation is also required. Sufficient time recording devices and personnel are required to record elapsed time of each of the LRS phases.

4.1.4. Threat Representation. The test facility must also be able to simulate various environmental threats (sea state, water clarity, currents) to the launch and recovery operations of the system. Radiated noise testing will determine system stealth to protect from acoustic threats.

4.1.5. Test Targets and Expendables. The LRS will not use any expendable test articles. The test ready LRS will be a fully functional system on an operational VIRGINIA Class Block III submarine. UUVs used for LRS testing will be actual mission capable UUVs.

4.1.6. Operational Force Test Support. A VIRGINIA Block III submarine will be required for a 16 week outfitting period and 2 week testing period. DOD Communication satellites with submarine an UUV communications will be required for the 2 week testing period. An operational support surface ship will also be required for the 2 week testing period.

4.1.7. Simulations, Models and Testbeds. Early stage modeling and simulation was used to select concept alternatives. The LRS is a mechanical system and limited, if any modeling and simulation will be required for follow on testing. All components can be mechanically or electrically tested in their environment or simulated environment.

4.1.8. Joint Mission Environment. Operational testing of the LRS will make use of long range ISR UUVs. For some aspects of testing, dedicated UUV mission planning support will be required in the instances where a UUV is given an updated recovery location from the original uploaded mission plan.

4.1.9. Special Requirements. The LRS is not scheduled to use any special instrumentation or analysis. The testing strategy makes use of testing methods and instrumentation that is already developed and proven by the U.S. Navy.

4.2. Test and Evaluation Funding Summary. NO LFT&E test are required for the LRS.

APPENDEX F – DECISION AND SCORING TABLES

The decision scoring tables below show the weighted averages of the end users priorities with respect to system capabilities. The "Maximax" principle, picking the highest scoring value, was used in selection of the recommended alternative. Where only "0" is assigned for a particular category, either there is no rationale to differentiate the design characteristic from one alternative to another or other categories already encompass the information.

Design Characteristic	Weight
Launch Speed	2.3
Recovery Speed	2.3
Reliability (Success)	1.7
Operational Depth	1.7
Charging Capacity	1.3
Acoustic Signature (Detection)	0.9
Shock Resistance	0.9
System Weight	0.6
Payload Space	0.4
Data Transfer Rate/Clarity	0.4

Table F-1 Launch Speed Scoring Table

Launch Speed	Risk	Performance (x2)	Interfaces	Reliability	Safety/ Usability (x2)	Logistics	Use (Sum of Ranks)
Baseline	1	1	5	1	1	5	36.8
ALT-1	5	5	2	5	3	3	71.3
ALT-2	5	4	2	2	3	3	59.8
ALT-3	5	3	2	3	3	3	57.5
ALT-4	3	2	1	4	5	1	52.9

Table F-2 Recovery Speed Scoring Table

Recovery Speed	Risk	Performance (x2)	Interfaces	Reliability	Safety/ Usability (x2)	Logistics	Use (Sum of Ranks)
Baseline	1	1	1	1	1	5	27.6
ALT-1	5	4	5	5	5	1	78.2
ALT-2	2	2	2	2	2	4	41.4
ALT-3	5	3	3	4	3	3	62.1
ALT-4	5	5	5	3	5	1	78.2

Table F-3 Reliability Success Scoring Table

Reliability (Success)	Risk	Performance (x2)	Interfaces	Reliability	Safety/ Usability (x2)	Logistics	Use (Sum of Ranks)
Baseline	1	1	0	5	1	5	25.5
ALT-1	3	5	0	3	4	2	44.2
ALT-2	5	2	0	2	2	4	32.3
ALT-3	3	3	0	4	3	3	37.4
ALT-4	3	4	0	1	5	1	39.1

Table F-4 Operational Depth Scoring Table

Operational Depth	Risk	Performance (x2)	Interfaces	Reliability	Safety/ Usability (x2)	Logistics	Use (Sum of Ranks)
Baseline	1	0	0	1	1	0	6.8
ALT-1	3	0	0	3	4	0	23.8
ALT-2	4	0	0	4	2	0	20.4
ALT-3	2	0	0	2	3	0	17
ALT-4	5	0	0	5	5	0	34

Table F-5 Charging Capacity

Charging Capacity	Risk	Performance (x2)	Interfaces	Reliability	Safety/ Usability (x2)	Logistics	Use (Sum of Ranks)
Baseline	1	1	1	3	3	3	20.8
ALT-1	3	3	3	5	1	5	31.2
ALT-2	3	4	3	5	1	5	33.8
ALT-3	3	2	3	5	1	5	28.6
ALT-4	5	5	5	1	5	1	41.6

Table F-6 Acoustic Signature Scoring Table

Acoustic Signature	Risk	Performance (x2)	Interfaces	Reliability	Safety/ Usability (x2)	Logistics	Use (Sum of Ranks)
Baseline	1	1	2	3	0	5	11.7
ALT-1	5	5	3	5	0	1	21.6
ALT-2	2	2	5	5	0	3	17.1
ALT-3	4	4	4	5	0	3	21.6
ALT-4	3	3	1	1	0	1	10.8

Table F-7 Shock Resistance Scoring Table

Shock Resistance	Risk	Performance (x2)	Interfaces	Reliability	Safety/ Usability (x2)	Logistics	Use (Sum of Ranks)
Baseline	1	1	1	1	1	5	10.8
ALT-1	3	5	5	3	4	1	27
ALT-2	4	2	3	4	2	3	19.8
ALT-3	2	4	3	2	3	3	21.6
ALT-4	5	3	5	5	5	1	28.8

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